Atomic Energy Control Board
P.O. Box 1046
Ottawa, Canada
K1P 5S9

Commission de contrôle de l'énergie atomique
C.P. 1046
Ottawa, Canada
K1P 5S9

INFO-0173

ELECTROSTATIC PURIFICATION OF URANIUM MINE STOPE ATMOSPHERES

by

SENES Consultants Limited

A report prepared for the
Atomic Energy Control Board
Ottawa, Canada

Canada

January 1986

Research report

86-04214/

ACKNOWLEDGEMENTS

The project manager for this study was Mr. Glenn Case. Mr. J. D. Phyper was the principal investigator and the lead author. Dr. L. M. Lowe reviewed the report as well as preparing Chapter 8 dealing with the effect of precipitators on reducing exposure. Dr. D. B. Chambers assisted in the preparation and technical review of the report.

The assistance of Denison Mines Limited, Rio Algom Limited, Amok, Union Carbide Corporation and the Commissariat a l'Energie Atomique in providing information is gratefully acknowledged.

EXECUTIVE SUMMARY

Electrostatic precipitators have been and are currently being used to reduce levels of radioactive aerosols in uranium mine stope atmospheres.

Historically, while the electrostatic precipitators have been reported to be successful in reducing levels of radioactive aerosols many practical problems have been encountered with their use in the underground mine environment. Electrical short circuiting appears to have been the major problem with the use of precipitators in humid underground environments. On the basis of literature reviewed for this study it seems that the problems encounterd in the past can be overcome.

The most likely use of a precipitator in an underground uranium mine is to treat some or all of the air immediately upstream of a work station. The possible locations and uses of a precipitator would vary from work station to work station and from mine to mine.

The desirability and costs of using electrostatic precipitators to purify the air entering a work station are application specific. SENES Consultants therefore is not recommending for or against the use of electrostatic precipitators in undergound uranium mines. The information provided in this report can be used however to assist in such determinations.

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SOMMAIRE

Les précipatateurs électrostatiques sont couramment utilisés pour réduire la concentration des aérosols radioactifs dans l'atmosphère des chantiers des mines d'uranium.

Dans le passé, tout en montrant les performances satisfaisantes quant à la réduction de la pollution radioactive atmosphérique, les précipitateurs électrostatiques étaient sujets à des difficultés de fonctionnement dues à l'environnement souterrain. Les courts-circuits électriques ont été le problème majeur en atmosphère humide. D'après la documentation étudiée, il semble que les difficultés rencontrées dans le passé peuvent être surmontées.

L'usage le plus vraisemblable d'un précipitateur dans une mine d'uranium souterraine est de traiter tout ou en partie de l'air immédiatement en amont d'un lieu de travail. Les emplacements et usages possibles des précipitateurs pourraient varier de chantier à chantier et de mine à mine.

Les avantages et coûts de l'usage de précipitateurs électrostatiques pour purifier l'air entrant dans un chantier sont spécifiques à chaque cas. En conséquence SENES Consultant ne formule pas de recommandation, pour ou contre, l'usage de précipitateurs électrostatiques dans les mines d'uranium. Cependant, les informations contenues dans ce rapport peuvent aider à une prise de décision en ce domaine.

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1.0 INTRODUCTION

1.1 Overview

The atmosphere in underground uranium mines is complex. Gases and aerosols arise from various activities such as drilling, blasting, mucking, diesel engine exhaust and mechanical maintenance (including welding). Thus, in addition to radon gas and radon daughters, the mine atmosphere may include dust, oil droplets, water droplets, blasting gases, diesel exhaust and welding fumes. Where thorium is present in the ore or waste, thoron and thoron daughters will also be present in the mine atmosphere.

Various techniques are used to control the levels of mine air contaminants. The most common technique is the use of large volumes of fresh diluted air carefully distributed through the mine. In addition, water sprays are commonly used to suppress dust generation from mucking. In some instances coatings and sealants have been applied to exposed ore surfaces to reduce the flux of radon into the mine air.

Another technique which has found some application is the use of electrostatic precipitators to remove some of the aerosols from mine air. This report examines the theoretical basis for and experience with the use of electrostatic precipitators in underground uranium mines.

Much of the exposure associated with radioactive aerosols results from exposure to radon daughters. The majority of radon daughter atoms are formed in a charged state and as such are readily attached to various host particles present in mine air such as fumes, vapours, smoke, mist and dust. Because the majority of the daughter products in a mine environment are attached to host particles which can be charged (Bigu and Kirk, 1982), they can be removed from the air by the use of electrostatic precipitators which efficiently remove the host particles. It has also been suggested that the unattached fraction will be removed by an electrostatic precipitator (Pourprix et al., 1984). The net result is a reduction in the concentration of radioactive

aerosols and a reduction of the potential exposure.

Practical experience with precipitators in underground uranium mines is limited. During the 1970's and early 1980's, electrostatic precipitators were used extensively at underground uranium mines in the Uravan Mineral Belt in Colorado. The mines however, eventually phased out the use of the precipitators because of maintenance problems. In Canada, Denison mines currently uses electrostatic precipitators to treat welding fumes in the underground maintenance shops (Schryer, 1985). Electrostatic precipitators are also being used in pilot studies by the French Commissariat a l'Energie Atomique (CEA) to assess the removal efficiency of radioactive aerosols from uranium mine air. These pilot studies are being conducted at uranium mines in both France and Niger.

1.2 Study Objectives

The purpose of this study is to evaluate the practicality of using electrostatic precipitators to remove radioactive aerosols from underground uranium mines in Canada. The evaluation described in this report is based upon four objectives as outlined in the terms of reference by the Atomic Energy Control Board (AECB):

1. Review and critically assess the open literature on the use of electrostatic precipitation for removal of radioactive aerosols from the air in underground uranium mines. The assessment must include a discussion of the environmental parameters and their influence on the electrostatic precipitation process, identification and if given, the specifications of the precipitators used, the effectiveness of the precipitators for removal of radioactive aerosols, and the significance, quantitatively, of the aerosol removal to radiation dose of the miners.

2. Review and critically assess the air cleaning equipment and manufacturer's specifications for their industrial electrostatic precipitators.

3. Describe the designs and work environments of typical Canadian underground uranium mines.

4. Using the information derived from objectives 1 through 3, assess the feasibility, effectiveness and cost of using electrostatic purification of mine air in Canadian underground uranium mines.

In addition to the above, the AECB directed that the study was to be limited to an investigation of the developments in the field that have taken place since the preparation of a 1978 report entitled "Engineering Evaluation of Radon Daughter Removal Techniques" by D.B. Lindsay, J.R. Lawtor and I. Jasmani.

1.3 Report Organization

The remainder of this report is divided into the following sections.

Chapter 2 Canadian Underground Uranium Mine Environments describes the environments of several underground uranium mines in Canada. The environment in an underground mine can be considerably different than those that occur at more common industrial applications and needs to be considered in subsequent evaluations of performance.

Chapter 3 General Characteristics of Electrostatic Precipitators is a description of the mechanisms operating in precipitators that remove particulate matter and a review of two general types of electrostatic precipitators.

Chapter 4 The Influence of the Working Environment on the Operation of Electrostatic Precipitators describes how environmental conditions such as humidity and temperature influence the performance of electrostatic precipitators.

Chapter 5 The Efficiency of Electrostatic Precipitators in the Removal of Radioactive Aerosols discusses the theoretical and observed efficiencies of electrostatic precipitators in underground uranium mines. The performances of electrostatic precipitators that have been observed in uranium mines outside Canada are reviewed along with the operating environments of those mines.

Chapter 6 Review of Available Electrostatic Precipitators presents a review of the currently available electrostatic precipitators and includes unit costs and manufacturers' specifications.

Chapter 7 Costs of Using Electrostatic Precipitators presents estimates of the capital and operating costs of using electrostatic precipitators in underground Canadian uranium mines.

Chapter 8 Anticipated Radiation Exposure and Dose Reduction discusses the effectiveness of electrostatic precipitators in the reduction of radiation exposure and dose. The current conditions in Canadian underground uranium mines are discussed as well as the effects of attached and unattached radon daughter fractions. The relationship between efficiency of purification and exposure and dose reduction is presented.

Chapter 9 Summary presents an assessment of the overall costs, operational problems, effectiveness and potential locations for using electrostatic precipitators as applied to the removal of radioactive aerosols from Canadian underground uranium mine atmospheres.

Appendix A Survey Results lists the companies surveyed and whether or not they produce an appropriate electrostatic precipitator.

Appendix B Efficiency Model describes the method of determining the effective migration velocity used in the Deutsch equation and lists the computer code for a generic model of precipitator efficiency.

2.0 GENERAL CHARACTERISTICS OF ELECTROSTATIC PRECIPITATORS

2.1. Basic Principles of Operation

2.1.1 Introduction

The removal of airborne particulate matter by an electrostatic precipitator is based on two consecutive processes that occur between particles and ions in a strong electric field.

The first process, commonly referred to as "charging", is the imparting of an electrostatic charge to a particle in a gas stream. Charging is almost always accomplished by a corona discharge, a mechanism that forms ions in a gas, and usually occurs within a few-hundredths of a second after the gas enters the precipitator. The second process, particle collection, occurs by the action of coulomb electric forces on the particles. The forces cause the particles to move toward the collecting electrodes.

The principles of corona discharge, charging and particle collection are described below.

2.1.2 Corona Discharge

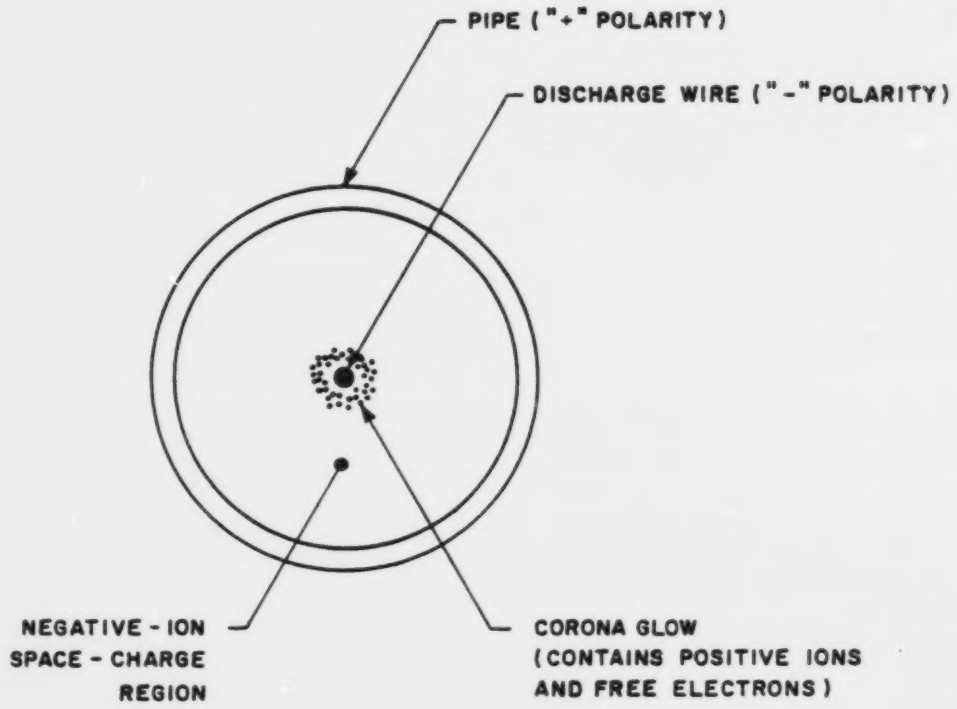
The formation of a corona requires a few free electrons plus the presence of a strong electric field. The corona is formed by applying a large potential difference between an active high-voltage electrode, which is a fine wire called the discharge electrode or ionizer wire, and a passive ground electrode, which can be a plate or a pipe.

Negative Corona

Electrostatic precipitators use either positive or negative corona discharges. Figure 2.1 illustrates a negative corona discharge. Electrons released from or near the wire surface move in the intense electric field of the corona glow

FIGURE 2-1

NEGATIVE CORONA DISCHARGE



SOURCE: ADAPTED FROM CALVERT AND ENGLUND, 1984

region and produce enormous numbers of additional electrons, in a process called an electron avalanche, by impact ionization with gas molecules. These additional electrons are attracted to the outer positive polarity cylinder and attach to gas molecules in the passive region between the glow region and the pipe surface. The electron attachment occurs because free electrons in the relatively low electric field of the passive region attach to the gaseous molecules instead of producing further ionization. The passive zone typically has an ion density of 10^7 to 10^8 ions/cm^3 (Calvert and Englund, 1984).

When the electrons attach to gas molecules, negative ions are formed; which in turn attach to the particles and cause the particles to be negatively charged.

The electron impact ionization in the glow region produces a positive ion for every electron generated. These positive ions move to the wire where they release new free electrons by impact with the wire surface or by photoelectric effect in the gas or at the wire surface. This regenerative action of the positive ions in releasing new electrons at the wire ensures that the corona discharge will be self-maintaining (Calvert and Englund, 1984).

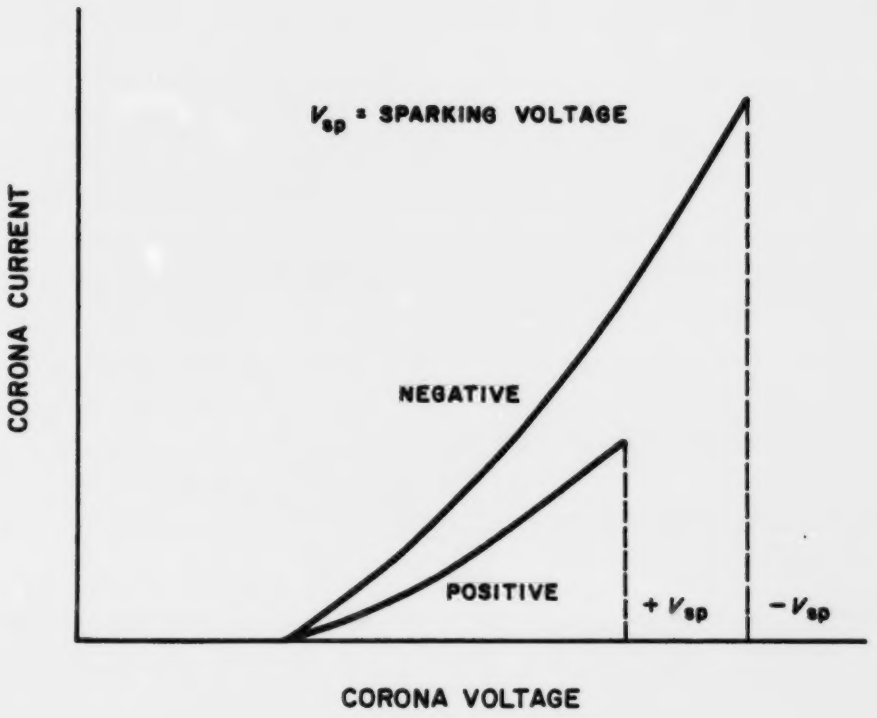
A negative corona type of precipitator can operate at a higher voltage, and hence a higher collection efficiency, without sparking than a precipitator with a positive corona discharge (Figure 2.2). The spark between the discharge and grounding electrode causes a breakdown of the corona gap.

Positive Corona

For the formation of a positive corona, the wire is positively charged relative to the ground electrode; the electrons then migrate toward the wire. The region of large field strength is confined to the corona region and the field strength is greatest at the wire surface. The electron avalanche commences at the edge of the corona region and proceeds all the way to the wire surface. Since there is no opportunity for these electrons to be absorbed, no negative ions are produced. However, there is a large number of positive ions produced in the avalanche process and these migrate out of the

FIGURE 2·2

CORONA CURRENT-VOLTAGE CHARACTERISTICS FOR NEGATIVE AND POSITIVE CORONA IN AIR



SOURCE: ADAPTED FROM CALVERT AND ENGLUND, 1984

corona glow region toward the pipe surface (Crawford, 1976).

These positive ions then attach to the particles present in the gas stream, charging them positively. The free electrons which rush into the wire are carried away as a current in the wire.

The number of free electrons formed by impact ionization, although sufficient to start a positive corona, is not enough to sustain it. The additional free electrons which are required are formed near the edge of the corona by ultraviolet emission from the corona itself (Crawford, 1976).

Electrostatic precipitators with positive corona discharge produce less ozone than precipitators with negative corona discharge, and thus are preferred for the cleaning of ventilation air in offices and houses (Calvert and Englund, 1984).

Back Corona

If a dust layer builds up on the grounding electrode, the corona current must pass through it to reach ground potential. In most instances this causes no difficulty but if the resistivity of the dust layer is greater than about 10^{11} ohm cm, the electric field strength in the dust, which is proportional to the resistivity of the dust for a given ion current density, may become large enough to result in a condition similar to dielectric breakdown as described below (Pontius and Bush, 1984).

When localized channels of high current density penetrate the dust layer, the result is a convergence of the electric field in the gas adjacent to the layer. This electric field can become great enough to sustain a corona discharge called the back corona. It is opposite in polarity to the primary corona. The back corona has the overall effect of degrading the particle charging mechanisms (Pontius and Bush, 1984).

2.1.3 Particle Charging

Some radioactive aerosols carry charges but these charges are too small for effective collection via electrostatic precipitation. Hence, it is essential to provide a high degree of charging to ensure a high collection efficiency. As previously described, charging is accomplished by passing the particle through a corona region.

There are two distinct particle charging mechanisms in the corona field of a precipitator: field charging and diffusion charging. Field charging is the process in which ions, acted on by the force of the applied electric field, are driven to the particles. Field charging is predominant for particles larger than 0.5 μm in diameter.

Diffusion charging occurs when the ions collide with the particles because of the ions random motion. The random motion is determined by the thermal energy of the ions. The diffusion process is predominant for particles smaller than about 0.2 μm in diameter. In the particle size range of 0.2 to 0.5 μm both field charging and diffusion charging are important (Calvert and Englund, 1984).

2.1.4 Collection Process

The second process that takes place in an electrostatic precipitator is referred to as "collection". This process occurs when an electric field, applied to the gas stream, exerts an attractive force on the charged particles causing them to migrate at right angles to the direction of gas flow toward the oppositely charged-electrode (the collecting electrode). The velocity at which the particles move toward the collecting electrodes is determined by the balance between the electric forces and the drag on the particles arising from the viscosity of the gas between the electrodes.

Re-entrainment, the movement of previously collected particles back into the gas stream, may result from direct scouring of the collecting electrode surfaces by the gas stream, from re-dispersion of collected particles during

the cleaning of the electrodes, and during removal of collected dust from the hopper. The hopper is a dust collection vessel located beneath the collector section. These three types of re-entrainment are closely related to the patterns and characteristics of the gas flow through the precipitator. Increased dust losses and poor performance can result from an uneven gas velocity distribution and rough, turbulent flow (Calvert and Englund, 1984).

Good gas flow patterns based on gas flow model studies, avoidance of gas by-passing the electrodes, and effective hopper emptying methods are among the preventive measures that can be taken to minimize re-entrainment (Calvert and Englund, 1984).

2.1.5 Removal of Collected Particles

To remove accumulated dry particles, the electrode is cleaned by jarring or vibrating the collection plates. This is referred to as "rapping". The collected material falls into a hopper. The rapping intensity should be great enough to remove a significant fraction of the collected material but not so large as to propel material back into the main gas stream.

For very sticky or highly resistive particulate material, it may be necessary to wash the collecting plates. This can be accomplished by fine water jets which sweep the surface of the plates in a swirling action as the jet moves continually back and forth.

Some manufacturers have designed their precipitators to run either intermittently or continuously wet. This allows the unit to be washed while in operation. As a result, downtime for washing is eliminated. Advantages of using this equipment include the insensitivity of the precipitator to wetness and the reduction of re-entrainment problems due to highly resistive or highly conductive materials. As soon as a particle is collected, it is washed away.

2.2 Types of Electrostatic Precipitators

2.2.1 Two-Stage Type

Two-stage electrostatic precipitators are used routinely for air-conditioning applications and usually employ a positive corona to minimize ozone production.

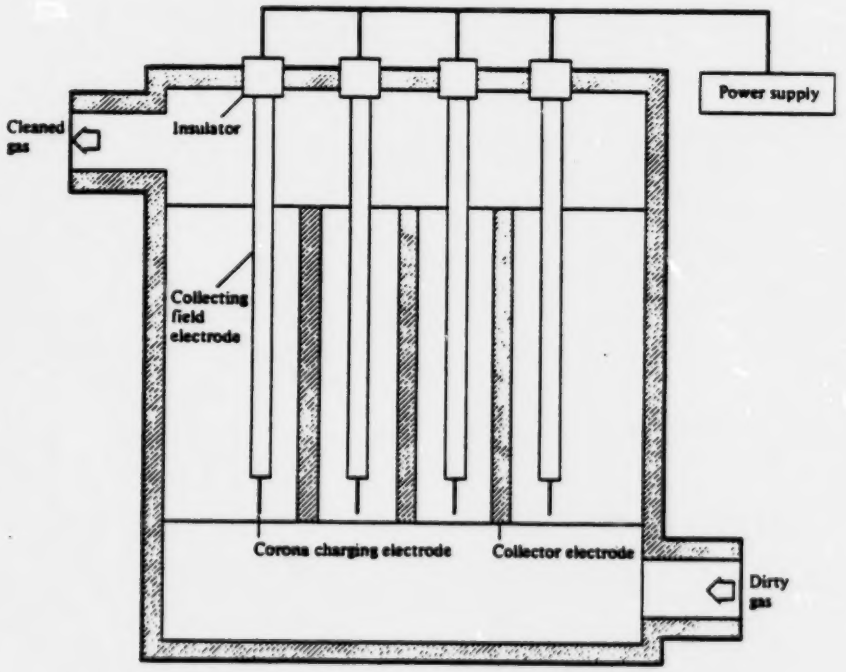
In two-stage precipitators, separate pairs of electrodes are employed for the particle charging and the collection functions. The first pair of electrodes are used in the corona section, which imparts a charge to the particles. This section is short, thereby providing a residence time of only a fraction of a second so that very little collection takes place on the grounding electrode resulting in a lower probability of a back corona discharge. In the second section, an electric field is maintained between the collecting-field electrode and the collector electrode.

In a cylindrical two-stage precipitator, the corona electrode is located at the bottom of the collector cylinder (See Figure 2.3). It consists of a small-diameter wire which is attached directly to the collecting-field electrode. The smaller diameter of the corona electrode induces the formation of a corona, which is absent from the collecting-field electrode due to its larger diameter. In other cases, the corona electrode and the collecting-field electrode are charged to different voltages by separate power supplies, with the collecting-field electrode having the lower voltage. The collector electrode, which is normally grounded, extends over both the charging and collecting sections (Crawford, 1976).

In a parallel plate two-stage precipitator, the corona electrodes consist of vertical wires (Figure 2.4). The collecting-field electrode and the collector electrode are parallel plates. The collector electrode, which is normally grounded, extends over both the charging and collecting sections and has the same potential in both sections. Both the corona and collector sections have separate power supplies enabling the corona electrode to be maintained at

FIGURE 2·3

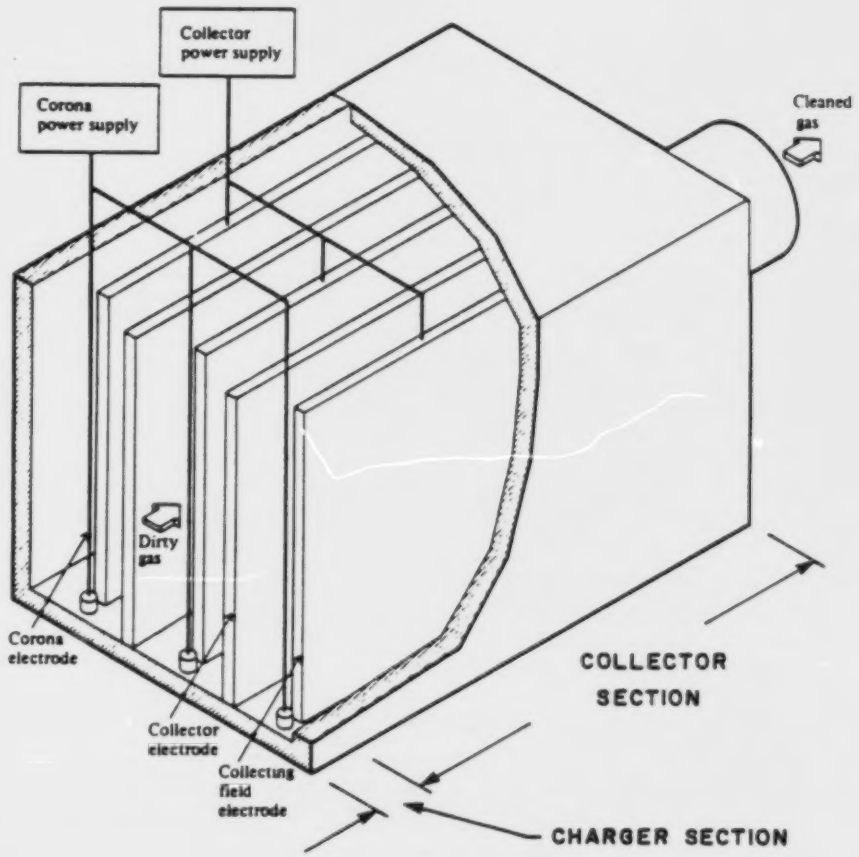
CYLINDRICAL TWO-STAGE ELECTROSTATIC PRECIPITATOR



SOURCE: CRAWFORD, 1976

FIGURE 2·4

PARALLEL-PLATE TWO-STAGE ELECTROSTATIC PRECIPITATOR



SOURCE: ADAPTED FROM CRAWFORD, 1976

a higher voltage than the collecting field electrode (Crawford, 1976).

2.2.2 Single-Stage Type

When used to treat large volumes of gas, two-stage units become excessively heavy because of the large number of plates required. To permit a wider plate spacing and the use of fewer plates while retaining a high efficiency the particles must be charged more effectively. This is accomplished by use of charging wires set in rows between and parallel to the plates. The separate charging section can then be eliminated.

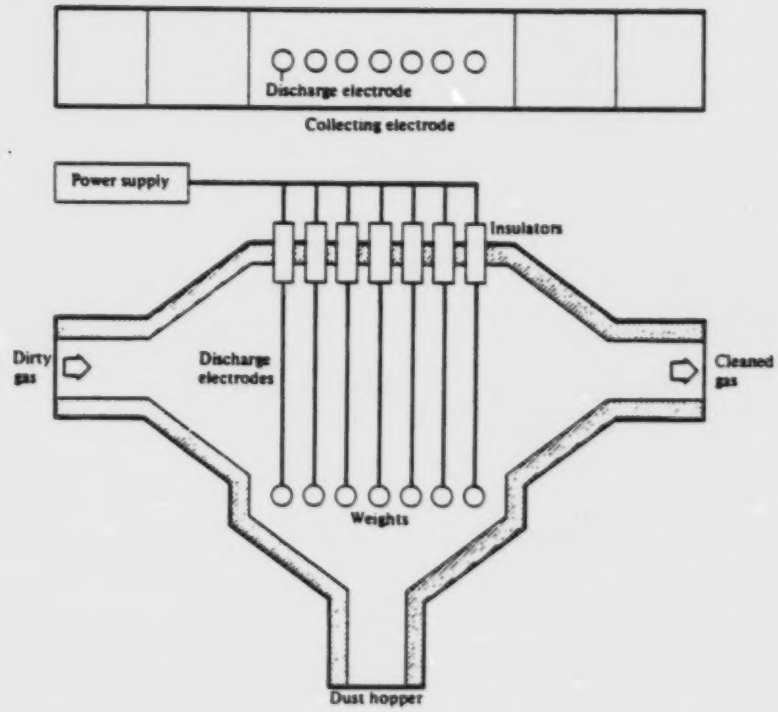
When the same pair of electrodes are used for both the charging and collecting functions, the precipitator is referred to as a single-stage precipitator. Single-stage units are generally operated with negative corona and are used in the control of air pollution from process and furnace gases. As previously mentioned, a negative corona allows for a higher collection efficiency than a positive corona, without sparking.

A parallel-plate, single-stage precipitator is shown in Figure 2.5. In this precipitator, the gas flows between two vertical parallel plates between which are suspended a number of vertical wires held in place by weights attached at the bottom. An electric field is maintained between the wires and the plates.

Figure 2.6 shows a cross-sectional view of a cylindrical, single-stage electrostatic preciptator. As the gas flows upward, it passes through the electrostatic field. The electrostatic forces cause the dust particles to migrate to the collection electrodes where they accumulate.

FIGURE 2·5

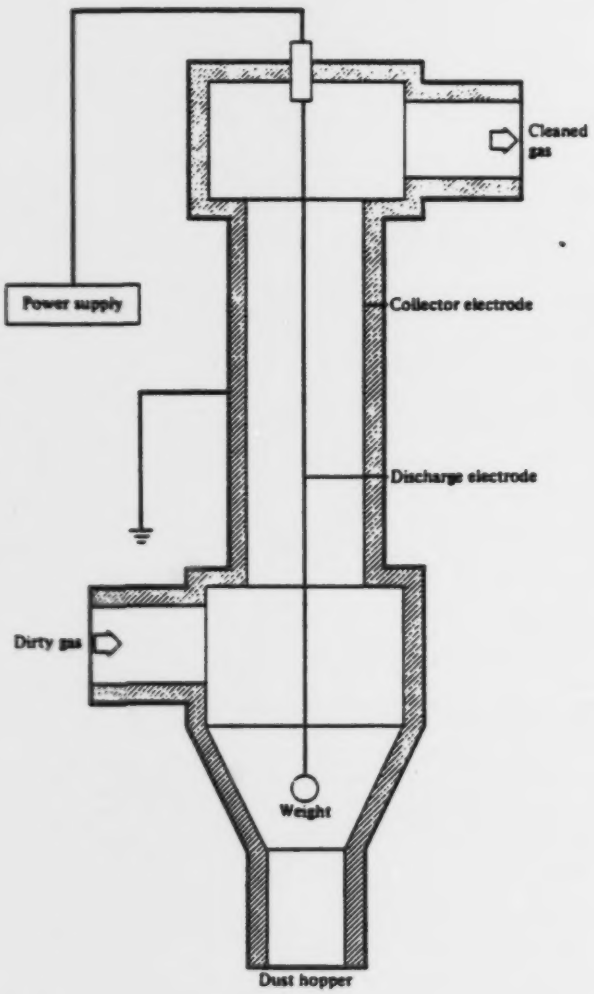
PARALLEL-PLATE SINGLE-STAGE ELECTROSTATIC PRECIPITATOR



SOURCE: CRAWFORD, 1976

FIGURE 2·6

CYLINDRICAL SINGLE-STAGE ELECTROSTATIC PRECIPITATOR



SOURCE: CRAWFORD, 1976

3.0 THE INFLUENCE OF THE WORK ENVIRONMENT ON THE OPERATION OF ELECTROSTATIC PRECIPITATORS

3.1 Introduction

Field and laboratory studies have indicated that several factors can influence the performance of electrostatic precipitators in the mine environment. These include relative humidity, temperature, and dust characteristics. In addition, the air flows, dimensions of passageways, and configurations of individual mines affect the potential application of electrostatic precipitators. The following sections describe the roles that these factors have been observed to play in field and laboratory studies.

3.2 Some Influential Factors

Available information on actual experience with the effects of relative humidity, temperature and the characteristics of mine dust on the use of electrostatic precipitators is reviewed in the following sections.

3.2.1 Relative Humidity

High relative humidity can affect a precipitator's performance by causing sparking and electrical short circuits in the precipitator. As discussed in Section 2.1.2, sparking (also called arcing) can occur in the charging section between the charging electrode and grounding electrode. It interferes with the operation of the precipitator by causing a breakdown in the corona gap.

Sparking has been observed under relatively humid conditions in mines in France and Niger (Pourprix et al., 1984). High voltage power supplies were protected against accidental discharges and were not damaged. To protect power packs from damage during arcing, a "current limiter" can be employed in the circuit.

During tests of electrostatic precipitators at a uranium mine in Colorado,

humid conditions resulted in the collection of condensate inside improperly sealed equipment and caused short circuits. According to manufacturers, currently available types of precipitators are made with a water tight seal and should not experience short circuiting (Rogers, 1985).

Experimental results indicate that at electric fields used by precipitators, changes in relative humidity, from 0 to 90%, have no effect on the collection of radioactive decay products (Dua et al., 1983). No information was cited on the effects on collection efficiency due to changes in relative humidity in the range of 90 to 100%.

3.2.2 Temperature

Temperature variations can affect precipitator performance. Relatively large temperature variations can affect the electrostatic resistivity of the dust collected on the plates. The resistivity of the dust layer is important since a high resistance will reduce the efficiency of collection and hence the efficiency of the precipitator. Typically, the electrical resistivity of particles is inversely related to temperature (Pontius and Bush, 1984).

Temperature variations of just a few degrees can affect precipitator performance; they can cause pronounced convective flows in poorly ventilated dead-end work areas. The convective flows can increase the mass transfer coefficient and hence the release of radon thereby affecting the downstream radon daughter concentrations. Higher radon daughter concentrations require greater precipitator capacity if air quality is to be maintained (Swindle, not dated).

The extent of convective flow in dead-end workings is a function of the season of the year, geometry of the workings and ventilation rate. In summer, convection is greatest in dead-end work areas that are inclined upward from the airways, and in winter it is greatest in dead-end work areas that are inclined downward below the airways (Swindle, not dated). If an area is well ventilated the convective flow should not be a factor.

3.2.3 Dust Concentration and Size Distribution

Dust size determines, in part, the migration velocity (see Chapter 5.1) to the collection plate and thus the efficiency of purification of an electrostatic precipitator. Figure 3.1 shows how the collection efficiency of electrostatic precipitators vary as a function of particle size.

The concentration of particles in an underground uranium mine influences the frequency that the collector plates need to be cleaned. The higher the concentration of dust, the higher the frequency of cleaning. The dust concentration in a mine can be affected by several operations, an example of which is blasting. Blasting will produce a very heavy, short-term dust load.

3.2.4 Other Factors

Other factors can influence the performance of an electrostatic precipitator in an underground uranium mine. For example, the resistivity of the dust will influence the collection efficiency and frequency of cleaning. The higher the resistance, the more frequent the washing, the greater the probability of re-entrainment, and the higher the frequency of sparking. No information has been found in the literature on the resistivity of dust in an underground uranium mine.

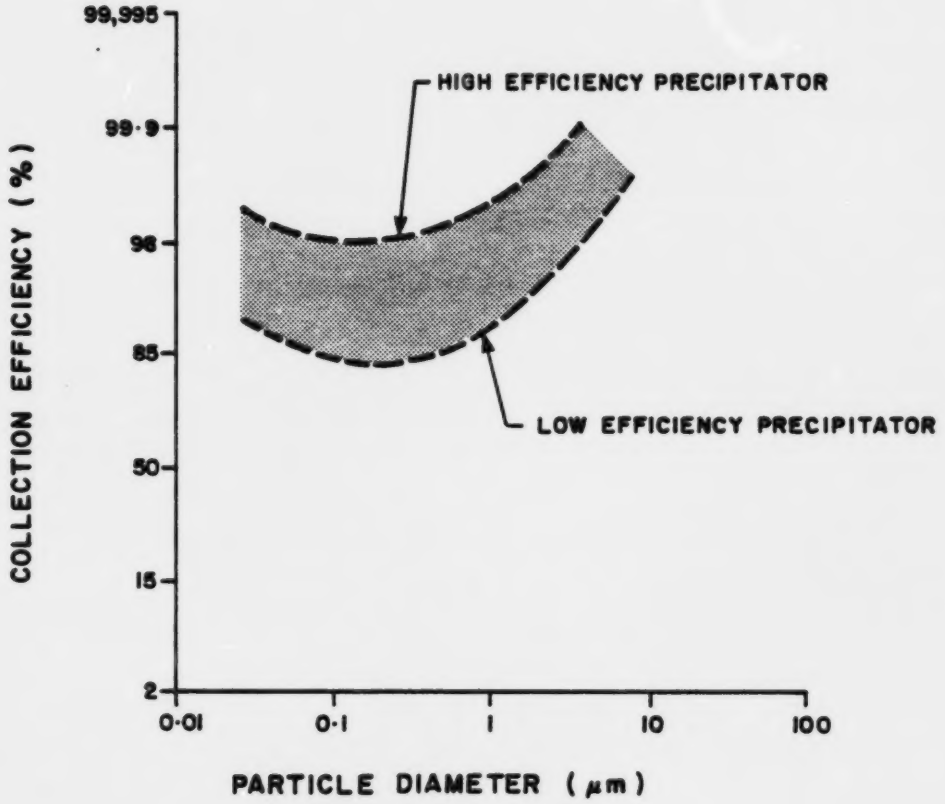
Another factor which will influence the efficiency of collection is the concentration of hydrocarbons such as those arising from diesel fumes. Hydrocarbon deposition on the plates will form a resistive layer which will reduce the electric field of the collector. The presence of diesel exhaust was observed to increase the required cleaning frequency of the precipitators at mines in Colorado (Beverly, 1985).

3.3 Potential Application of Electrostatic Precipitators in Underground Canadian Uranium Mines

As noted previously, air flow rates, passageway dimensions and other factors

FIGURE 3·1

EFFICIENCIES OF ELECTROSTATIC PRECIPITATORS* AT DIFFERENT PARTICLE SIZES



NOTE:

* FIGURE ILLUSTRATES RANGE OF TYPICAL COLLECTION EFFICIENCIES OF SINGLE-STAGE AND DOUBLE-STAGE PRECIPITATORS

SOURCE: ADAPTED FROM HOWES, 1982

can influence the way in which electrostatic precipitators can be used in underground uranium mines. This section outlines some of these factors and suggests, for purposes of illustration only, some ways in which electrostatic precipitators could be used in underground Canadian uranium mines. Their use in actual situations would have to be examined on a case by case basis.

Specific data related to factors such as environmental conditions, ventilation flows, and mine configuration are provided in Chapter 4 for three underground uranium mining operations.

3.3.1 Air Flow Rates and Mine Configuration

The ventilation system in an underground mine can be subdivided into primary and auxiliary systems. The primary system is used to ventilate the main passageways. Auxiliary ventilation is used for the ventilation of working places in mines in which the primary ventilation airstream is inadequate or unavailable. Two applications of auxiliary ventilation in mining are to ventilate dead-end workings and to provide supplemental flow to assist a portion of the primary ventilation network, as in booster ventilation (Hartman, 1982).

The configuration of a mine is a major determining factor on the way(s) that stopes (work areas) are ventilated. In some mines the stopes are dead-end workings, so auxiliary ventilation systems are used to feed air into the stopes from the primary ventilation system. In other mines the stopes are open at both ends and the primary ventilation air is passed through the stope; hence, little if any auxiliary ventilation is required. Auxiliary ventilation is used at these mines during stope development. In the above-mentioned mines, auxiliary ventilation systems are used to ventilate lunch rooms and maintenance shops.

In practice, air purification systems can be provided to manage the air quality for an individual, a room or work area, or an entire ventilation system (Pourprix et al., 1982). The quality of air entering such work areas

or work stations is of prime concern and thus the location of the precipitator is important. A potential location for a precipitator treating auxiliary ventilation is shown in Figure 3.2. The precipitator, located in the drift, would purify the air before it is fed into a work area.

A second potential location is in a stope. In this location the precipitator could treat part of the primary ventilation flow. The precipitator would purify the air before it is fed to a work station.

The practicality of this location, in terms of factors such as possible damage by mining equipment and limited range of influence, may limit this type of application.

3.3.2 Dimensions of Passage Ways and Work Areas

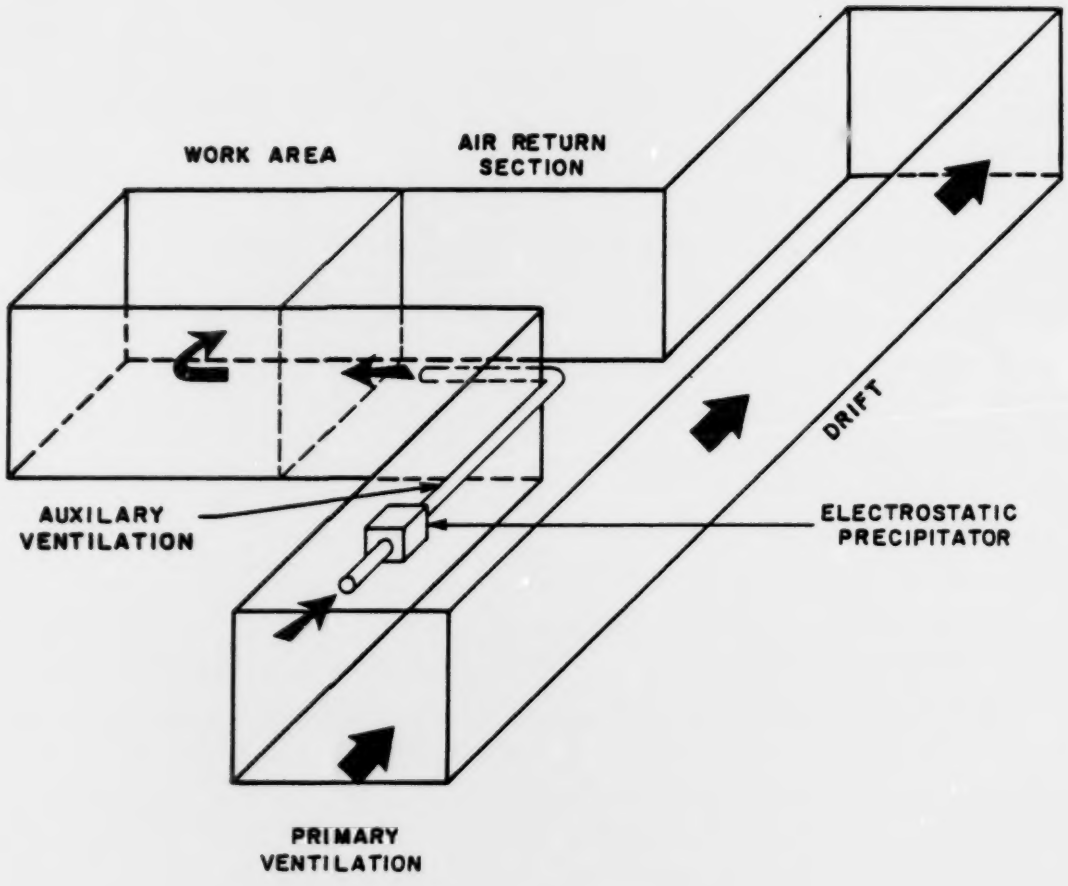
The cross-sectional area of a passage way or stope is a limiting parameter on the physical dimensions of an electrostatic precipitator. Obviously, it is undesirable to install electrostatic preciptators in a location that hinders the movement of workers or equipment.

For example, to treat an auxiliary flow rate of 7.1 m^3/s (15,000 cfm), which is representative of a mine in Elliot Lake, at an efficiency of 60 to 80% would require a precipitator approximately 2.5 m (8.2 ft) high, 1.0 m (3.3 ft) wide, and 1.2 m (3.9 ft) long. At this mine, the potential location of the precipitator could be in a drift (Figure 3.1). Since the average dimensions of a drift at this mine are 4.3 m (14 ft) high by 7.6 m (25 ft) wide, the placement of the precipitator in this drift could hinder the movement of equipment. One method to overcome the partial blockage of the passage way would be to cut a section out of the drift wall and place the precipitator in it.

When the primary ventilation flow is being used to ventilate a stope, the precipitator along with a fan could be located in the stope. Typical stope dimensions for one mine that employs this ventilation method are 3.0 m (10 ft)

FIGURE 3·2

POTENTIAL LOCATION OF ELECTROSTATIC PRECIPITATOR TREATING AUXILIARY VENTILATION



SOURCE: ADAPTED FROM OUDIZ et al, 1983

high by 15.2 m (50 ft) wide. It is anticipated that using a sled-mounted precipitator of the type previously described in the mine's stope may substantially hinder the movement of equipment or workers.

At another mine which passes primary ventilation through the stopes, the stopes are typically 2.0 m (6.6 ft) high by 2.5 to 3.5 m (8.3 to 11.6 ft) wide and the drifts are 3.0-3.5 m (9.9 to 11.6 ft) high by 3.0-5.0 m (9.9 to 11.6 ft) wide. The placement of a precipitator in either stope or drift would hinder the movement of equipment and workers. As previously noted, a section of the stope wall or drift wall could be cut out to accommodate the precipitator.

4.0 OVERVIEW OF ENVIRONMENTAL CONDITIONS AT CANADIAN UNDERGROUND URANIUM MINES

4.1 General

Environmental conditions at underground uranium mines are often considerably different than those at other industrial applications where electrostatic precipitators are more commonly used. This chapter discusses the mining methods and air environments in Canadian underground uranium mines. The levels and characteristics of the short-lived (primarily radon daughters) and long-lived radioactive aerosols which are present are of particular interest. The data presented in this chapter form the basis for evaluating the potential application of electrostatic precipitators in underground uranium mines in Canada.

4.2 Underground Mining Operations

The majority of uranium ore that has been recovered to date in Canada has been mined from underground deposits in Ontario and Saskatchewan. In Ontario, the underground uranium mines currently in production are those operated by Denison Mines Limited and Rio Algom Limited at Elliot Lake. These operations are mining relatively low grade ore, typically <0.1% U_3O_8. In Saskatchewan, Amok Limited operates an underground uranium mine at Cluff Lake with ore grades typically in the range of 0.3 to 0.5% U_3O_8. Amok Limited previously operated an open pit mine at Cluff Lake. In the open pit, ore grades were as high as 45% uranium (Bayda, 1977). Other uranium mines are in operation or, have operated in the past but these three operations form the basis of the descriptions presented in the rest of this chapter.

4.2.1 Mining Activities

While the ore recovery techniques used at any particular mine reflect many site-specific factors, there is a general sequence of ore-handling events followed at most mines. These include drilling and blasting, removing the

broken ore from the stopes and loading it into trains or trackless vehicles, crushing the ore underground, and hoisting the crushed ore to the surface. Figure 4.1 displays many of the features of a conventional (low grade) uranium mine.

Blasting is normally done at the end of a shift. Since it usually is several hours before the next shift enters the mine, the normal flow of ventilation air removes the high concentrations of dust and the noxious gases produced by blasting. Water sprays usually operate during and after blasting to suppress airborne dust.

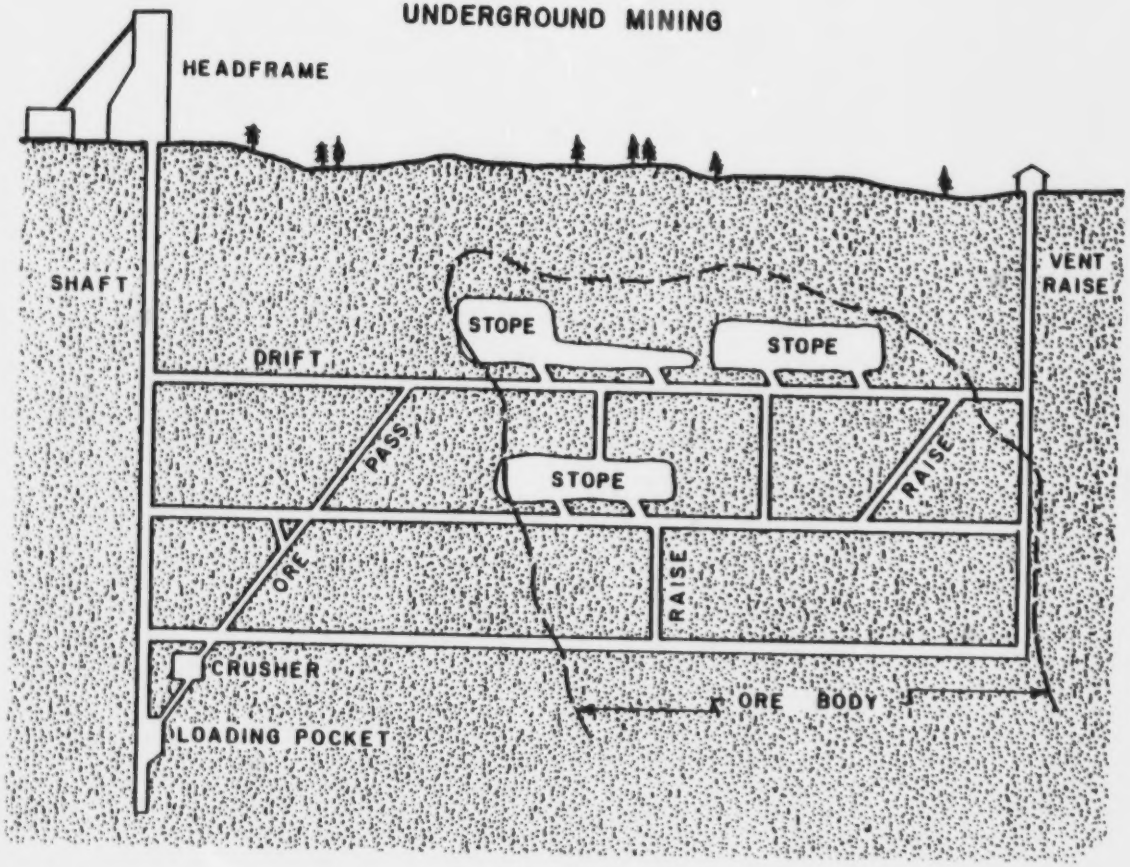
Following blasting, the miners remove (scale) loose rock from the roof of the work area as required, and load broken ore into rubber-tired or rail-mounted cars which transport the ore along the haulage ways. Both electric-powered and diesel trams are commonly used to haul broken ore from the chutes of the different stopes to the main ore pass. A crusher is generally located at the bottom of the ore pass where the ore undergoes primary crushing. The ore is then hoisted to the surface.

The major mining activities which generate airborne aerosols that would affect the operation of an electrostatic precipitator include: drilling operations which generate an aerosol composed of ore dust, oil droplets, water droplets, and other components; blasting, which produces an aerosol composed of pulverized and possibly vaporized ore and waste in addition to the blasting gases themselves; ore and waste handling operations such as mucking, hauling, and dumping which generate dust consisting of small particles, with compositions similar to the ore or waste; diesel exhaust, which contributes small-diameter particles (approximately less than 1 μm) composed mostly of carbon or soot, oxides of nitrogen and sulfur, carbon monoxide and numerous hydrocarbons; and welding, which generates small particles of welding flux components and metals.

In the past, the principal mining method used at the Rio Algom mines, in particular the Quirke Mine, was the conventional room and pillar stoping

FIGURE 4-1

CONVENTIONAL APPROACH
TO MINING LOW-GRADE URANIUM ORE



method, using jacklegs and slushers. More recently, a gradual changeover to trackless mining techniques has taken place in selected areas (Bell et al., 1985).

At the Denison operations, the basic mining technique has been the room and pillar method with development work carried out "in ore". Trackless mining with diesel powered rubber-tired vehicles has been used extensively. General descriptions of mining methods at Denison are provided elsewhere (e.g. MacLaren, 1977).

At the Amok operation, an "undercut and fill" technique is used. As of September 1985, one stope was being worked and a second stope was in the development stage (Bundy, 1985).

4.2.2 Ventilation and Flow Rates

At two of the underground operations (Mine A and B) the primary ventilation passes through the stopes. During stope development, auxiliary ventilation is used. In a third mine (Mine C), auxiliary ventilation is routinely used to ventilate the stopes.

Nominal air flow rates for these mines are listed in Tables 4.1 and 4.2.

4.2.3 Drift and Stope Dimensions

The dimensions of the drifts and stopes are affected by factors such as the ore thickness, dip angle and the mining method to be used. Tables 4.1 and 4.2 provide information on the drift and stope dimensions for the various mines.

4.3 Total Dust

Several studies have been made on the levels and nature of dust in underground uranium mines in the Elliot Lake, Ontario area (e.g. Bigu and Grenier, 1984; Duport and Edwardson, 1984; Bigu and Kirk, 1982; and Knight and Washington,

Table 4.1

NOMINAL VENTILATION PARAMETERS AT MINE A

Parameter	Area 1	Area 2	Area 3
Air Flow Rate into Stopes	2.36-18.9 m^3/s (5000-40,000 cfm)	0.47-14.2 m^3/s (1000-30000 cfm)	11.8 m^3/s (25000 cfm)
Air Flow Velocity into Stopes	0.25-1.02 m/s (0.83-3.34 ft/s)	0.25-0.51 m/s (0.83-1.67 ft/s)	0.64 m/s (2.1 ft/s)
Sill Drift Dimensions:			
- height	3.0 m (10 ft)	2.7 m (9 ft)	2.4 m (8 ft)
- width	3.0 m (10 ft)	3.0 m (10 ft)	7.6 m (25 ft)
or			
- height	3.0 m (10 ft)	4.6 m (15 ft)	
- width	6.1 m (20 ft)	6.1 m (20 ft)	
Stope Dimensions:			
- height	3.0 m (10 ft)	3.7 m (12 ft)	2.4 m (8 ft)
- width	15.2 m (50 ft)	18.3 m (60 ft)	15.2 m (50 ft)
- length	182.9 m (600 ft)	121.9 m (400 ft)	152.4 m (500 ft)
or			
- height	2.1 m (7 ft)		
- width	41.1 m (135 ft)		
- length	91.4 m (300 ft)		

Table 4.2

VENTILATION PARAMETERS AT MINE B AND MINE C

Parameter	Mine B	Mine C
Air Flow Rate into Stopes	5.7-14.2 m^3/s (12000-30000 cfm)	25.3 m^3/s (53600 cfm)
Drift Dimensions:		
- height	4.3 m (14 ft)	3.0 - 3.5 m (10-11.5 ft)
- width	7.6 m (25 ft)	3.0 - 5.0 m (10-11.5 ft)
Stope Dimensions:		
- height	2.4 m (8 ft)	2.0 m (6.6 ft)
- width	13.7-19.8 m (45-65 ft)	2.5-3.5 m (8.3-11.5 ft)
- length	91 m (300 ft)	10-15 m (33-49 ft)

1974). However, we are not aware of any published data concerning the workplace levels in the newly developed underground mine at Cluff Lake, Saskachewan. Thus the following descriptions of workplace environments in underground mines are largely based on data derived from mines in the Elliot Lake area.

4.3.1 Dust Loadings

Knight and Washington (1974) have reported data on the dust levels in an underground mine with a high quartz content in the ore. The mine studied by Knight and Washington made extensive use of diesel equipment and the authors note that a substantial fraction of the total respirable dust is combustible. (The authors note that dust sampling was carried out using modified size selective gravimetric samples manufactured by Casella. However, a specific definition of "respirable" is not provided. We take respirable to mean particles below 10 μm in aerodynamic diameter.)

Table 4.3 is adapted from Table 4 of Knight and Washington (1974). This table shows the compostion of respirable dust by type of mining operation. Mineral dust is that produced from the breakage of ore and waste rock. In the mines studied by Knight and Washington the mineral dust was about 65% quartz.

Table 4.3 shows that combustible dust is the major constituent in drilling and mucking. Both of these operations used compressed-air operated machines. Knight and Washington (1974) also noted that the combustible dust was derived from the lubricating oils. Combustible dust was also apparently significant in the car loading operation. (However, the authors report that because of the low weights of dust involved, both the contribution of combustible dust and non-mineral ash is questionable). Mineral dust was the main constituent in other areas.

Another early paper by Knight and Cochrane (1974) reported gravimetric dust sampling data for Elliot Lake mines as summarized in Table 4.4.

Table 4.3

COMPOSITION OF RESPIRABLE DUST PRODUCED IN EACH MINING OPERATION

Operation	Combustible %	Mineral %
Drilling	90	10
Blasting	12	37
Mucking	90	18 *
Slushing	11	100 *
Car Loading	40	36
Crushing	3	102 *
Ore and Waste Passes	1	92
Average of dust produced in working areas:	61	39

Reference

Knight and Washington, 1974

Note:

* Considered questionable by Knight and Washington (1974) because of weighing error.

More recently, Makepeace (1982) has analysed airborne dust data for two Elliot Lake Ontario mines. The study reports the relative dust exposures for nine different occupations. Makepeace reports total respirable dust levels that range from 0.33 mg/m^3 to 1.87 mg/m^3.

Duport and Edwardson (1984) note that the total dust mass concentrations are in the vicinity of 1 mg/m^3 throughout a mine of the Elliot Lake type, except at rock breaker and crusher locations where the dust concentrations are elevated as a result of the equipment operation.

Based on the foregoing, an underground dust concentration of about 1 mg/m^3 seems typical, at least for mines using diesel equipment. The data also suggest that about 60% of the dust would be combustible and the remaining 40% would be mineral dust.

4.3.2 Size Distribution

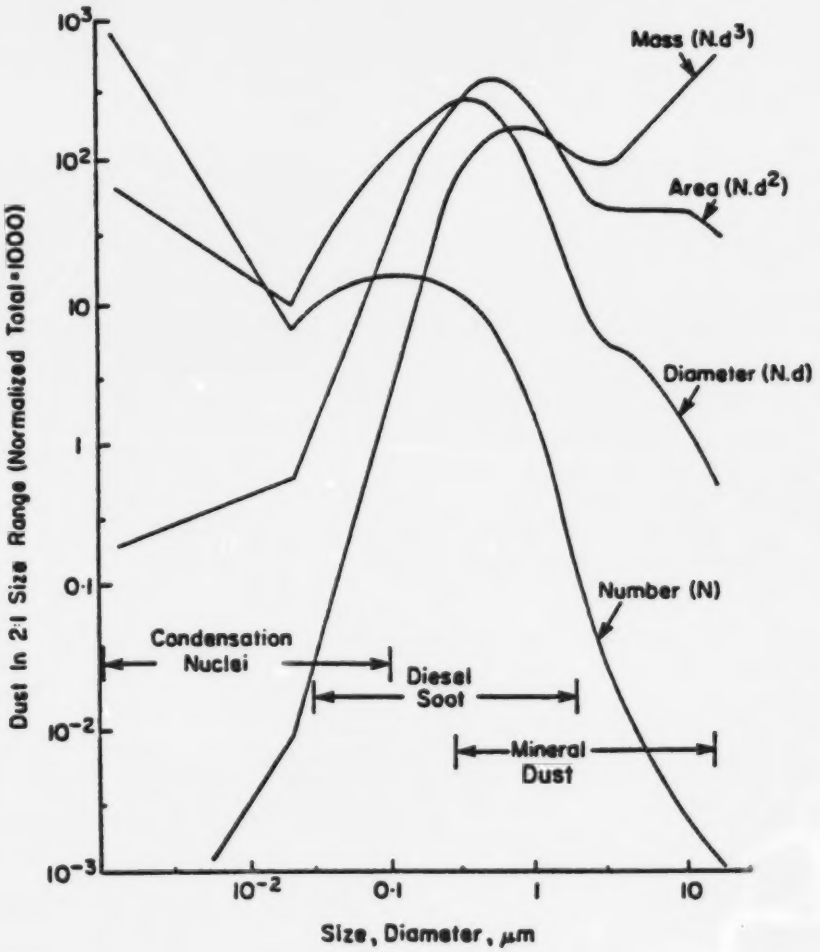
Several studies have been conducted on dust and aerosols in Canadian uranium mines. The mean aerosol concentration for underground uranium mines at Elliot Lake has been reported to range from 10^5 to 10^6 nuclei per cm^3 (Bigu and Kirk, 1982). The samples were taken at various locations in the mines, including near a crusher and at an exhaust site of nearby stopes. The sample locations were categorized in terms of "non-diesel" and "diesel" areas of the mine.

Figure 4.2 shows the calculated dust size distribution reported by Bigu and Grenier (1984). The size data are assessed by number N, diameter N.d, area $N.d^2$ and mass $N.d^3$. These results are reported to be based on simple assumptions and on experimental data collected with a horizontal eleutriator (2 μm to 10 μm) and other dust samplers. The Y axis indicates the number of particles (normalized for a total of 1000 particles) in the size range encompassing the X axis value to 2 times the X axis value.

The calculations shown on Figure 4.2 indicate that the condensation nuclei are the major contributors to number. Condensation nuclei are small particles

FIGURE 4·2

CALCULATED SIZE DISTRIBUTION OF MINE DUST AS ASSESSED BY NUMBER, DIAMETER, AREA OR MASS



SOURCE: ADAPTED FROM BIGU AND GRENIER, 1984

Table 4.4

GRAVIMETRIC DUST DATA FOR ELLIOT LAKE MINES

	Average Respirable Concentrations	
Operation	Total Dust (mg/m^3)	Quartz (mg/m^3)
drilling	1.02	0.06
loading/dumping	1.42	0.35
crushing	1.24	0.21
slushing	0.54	0.08

Reference

Knight and Cochrane, 1974

which serve as nuclei to initiate further processes, namely condensation and coagulation. Condensation nuclei originate primarily from the condensation and coagulation of hot, highly supersaturated vapours during combustion (NRC, 1978).

According to Bigu and Grenier (1984), the condensation nuclei are however only a minor contributor in terms of diameter (N.d), area ($N.d^2$) and mass ($N.d^3$). They suggest that diesel soot is a main contributor to diameter (N.d) and area ($N.d^2$) while mineral dust and non-soot diesel particulates are the main contributors to mass ($N.d^3$).

The distribution of the dust in Figure 4.2 indicates that in terms of number of particles most have a diameter of less than 1 μm while particles greater than 1 μm in diameter account for 50% of the aerosol mass (Bigu and Grenier, 1984).

Bigu and Grenier (1984) have determined the Mass Median Aerodynamic Diameter (MMAD) for the dust from two tests in an underground uranium mine to be 3.9 μm and 1.0 μm with geometric standard deviations of 10.9 and 5.2, respectively. The size distribution data from Bigu and Grenier (1984) shown on Figure 4.3 were collected with a 10-stage cascade impactor (0.1 μm to 28 μm) for the two runs.

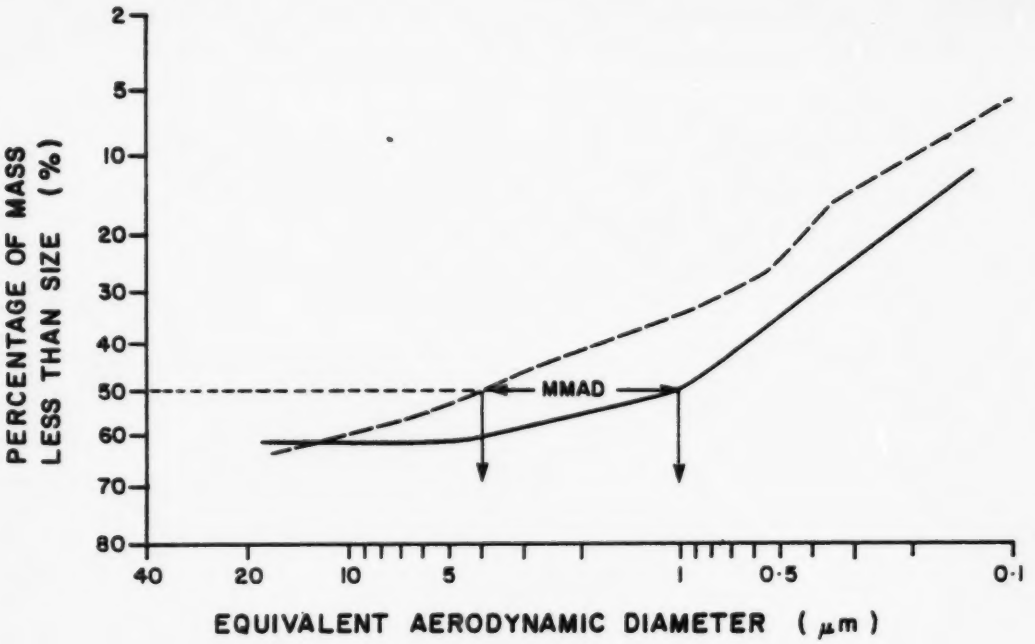
The difference between the two mine tests was attributed to changing underground conditions derived from different mining operations and the uncertainty in determining the mass (percentage of the total) of dust collected in a cyclone pre-separator (Bigu and Grenier, 1984).

Based on their review, Bigu and Grenier (1984) suggest that size distribution of dust in the range of 1 μm to 10 μm is bimodal. This view seems reasonable for mixed dust environments where there are contributions from both combustion sources (i.e. diesel) and mechanical sources (i.e. rock breaking activities).

The dust size ranges of radioactive dust and aerosols are discussed in

FIGURE 4·3

PERCENTAGE OF MASS LESS THAN SIZE VERSUS EQUIVALENT AERODYNAMIC DIAMETER FOR TWO UNDERGROUND URANIUM MINE DUST TESTS



NOTE:

1. ALSO SHOWN ON THE GRAPH IS THE MASS MEDIAN AERODYNAMIC DIAMETER (MMAD)
2. $D_{p,50}$ IS THE EQUIVALENT AERODYNAMIC DIAMETER (EAD) AT 50 % COLLECTION EFFICIENCY

SOURCE: ADAPTED FROM BIGU AND GRENIER, 1984

Table 4.5

RADIOACTIVE DECAY SERIES OF URANIUM-238 *

Historical Name	Nuclide	Half-Life	Principal Radiations
Uranium I	Uranium-238	4.51×10^9 y	alpha
Uranium X_1	Thorium-234	24.1 d	beta
Uranium X_2	Protactinium-234	1.17 min	beta
Uranium II	Uranium-234	2.47×10^5 y	alpha
Ionium	Thorium-230	8.0×10^4 y	alpha
Radium	Radium-226	1602 y	alpha
Radon	Radon-222	3.823 d	alpha
Radium A	Polonium-218	3.05 min	alpha
Radium B	Lead-214	26.8 min	beta, gamma
Radium C	Bismuth-214	19.7 min	beta, gamma
Radium C'	Polonium-214	164 us	alpha
Radium D	Lead-210	21 y	beta, gamma
Radium E	Bismuth-210	5.01 d	beta
Radium F	Polonium-210	138.4 d	alpha
Radium G	Lead-206	Stable	

* Minor radionuclides not shown.

Reference

Data from U.S. DHEW, 1970

Sections 4.5 and 4.6. The effect of particle size distribution on radiation exposure and dose is discussed in Section 8.2.

4.4 Temperature and Humidity

The temperature in an underground mine is a function of the particular season and location. At the Denison operation, the winter temperature is approximately 4°C, while summer temperatures range from 10 to 15°C (Schryer, 1985). A temperature range of 15 to 20°C in the summer and a winter temperature of typically 4°C have been reported for the Amok mine (Fundarch, 1985).

The relative humidity in an underground mine is also a function of the season. In the summer months the relative humidity is in the range of 90 to 100%, while in winter the humidity shows a wider variation, ranging from 30 to 100%. This wide range in winter is a result of the outside air being generally less humid (Bigu et al., 1980a; Bigu et al., 1980b).

4.5 Long-Lived Radioactive Dust

Ore dust in uranium mines contains Long-Lived Radioactive Dust (LLRD) from the uranium-238 decay series and in situations where thorium is present the dust contains radionuclides from the thorium-232 decay series. Many of the long-lived radionuclides are alpha emitters (see Tables 4.5 and 4.6). Data on LLRD in Canadian uranium mines are very limited.

4.5.1 Size Range

Few studies have been conducted on the physical characteristics of LLRD in Canadian underground uranium mines. The studies were carried out in uranium mines of widely different ore grades, mining practices and during the course of a number of mining operations.

In a study by Duport and Edwardson (1984), the physical characteristics of

Table 4.6

RADIOACTIVE DECAY SERIES OF THORIUM-232

Historical Name	Nuclide	Half-Life	Principal Radiations
Thorium	Thorium-232	1.41×10^{10} y	alpha
Mesothorium I	Radium-228	6.7 y	beta
Mesothorium II	Actinium-228	6.13 h	beta, gamma
Radiothorium	Thorium-228	1.91 h	alpha
Thorium X	Radium-224	3.64 d	alpha
Thoron	Radon-220	55 s	alpha
Thorium A	Polonium-216	0.15 s	alpha
Thorium B	Lead-212	10.64 h	beta, gamma
Thorium C	Bismuth-212	60.6 min	alpha, beta
Thorium C'	Polonium-212	304 ns	alpha
Thorium C"	Thallium-208	3.10 min	beta, gamma
Thorium D	Lead-208	Stable	-

Reference

Data from U.S. DHEW, 1970

LLRD were investigated in Canadian uranium mines and mills. The Mass Median Aerodynamic Diameters (MMAD) for the various underground locations are presented in Figure 4.4. In the study, the MMAD and Activity Median Aerodynamic Diameter (AMAD) were generally in the range of 2 to 10 μm with geometric standard deviations between 3 and 5. The authors suggested that a mean AMAD value of 5 μm is representative of all underground occupations, except for workers who spend most of their time in haulage and travelways, where the representative AMAD value is 10 μm. Figure 4.4 presents both MMAD and the AMAD as a function of mine location.

Bigu and Grenier (1985) conducted a similar study on LLRD. The average MMAD derived from their data was about 2.2 μm.

In both studies the size distribution analyses of radioactive dust, radioactive aerosols and non-radioactive dust were conducted by means of a 10-stage cascade impactor with glass fibre filters. In the absence of a cascade impactor calibration under actual mine conditions and because of the discrepency between theoretical and practical collection efficiency on glass fibre substrates, the above MMAD values can only be considered estimates.

4.5.2 Measured Radioactivity Levels

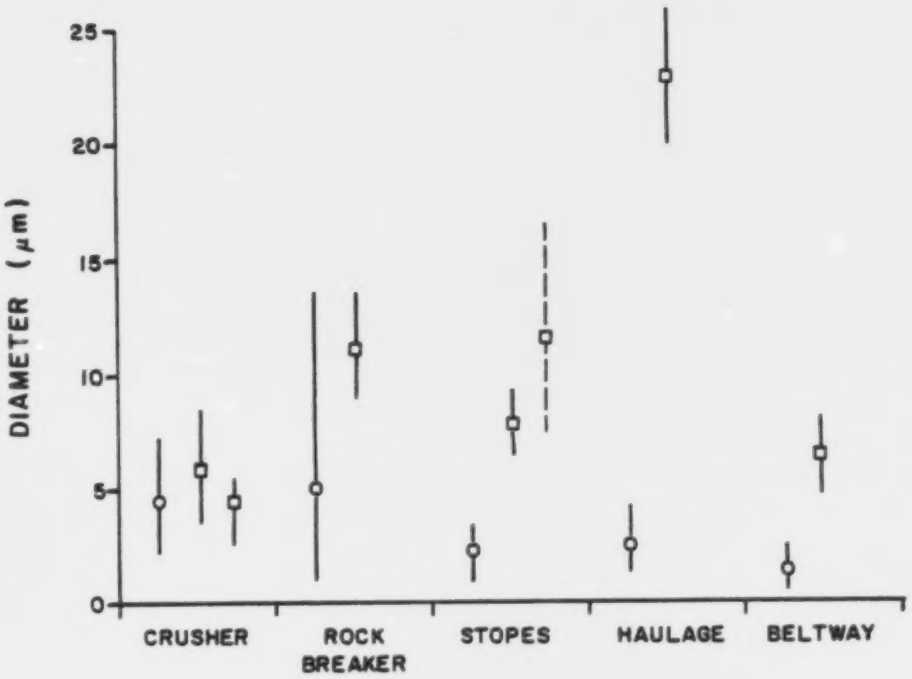
In the Duport and Edwardson (1984) study, the radon-222 emanation coefficients of uranium-bearing particles (the fraction that escapes the particle) were about 30% and the levels of alpha emitting dust ranged from 10 to 700 mBq/m^3 in the underground locations.

Bigu and Grenier (1985) reported an average AMAD value of 2.8 μm and an average alpha activity, corresponding to the LLRD, in the range of 50 to 80 mBq/m^3.

Several studies have shown that the specific activity (i.e. alpha activity per unit mass) remains nearly constant over the entire respirable dust size range of 1 μm to 10 μm (Knight et al., 1981; Bigu et al., 1981; Bigu et al., 1983).

FIGURE 4·4

MMAD AND AMAD IN UNDERGROUND LOCATIONS FOR LLRD



LEGEND:

- ○ MMAD
- □ AMAD
- ——— MINE A
- – – – – MINE B

SOURCE: ADAPTED FROM DUPORT AND EDWARDSON, 1984

This range better represents the LLRD than the short-lived radioactive aerosols, as discussed in Section 4.6.

4.6 Short-Lived Radioactive Aerosols

4.6.1 Radionuclides of Interest

The short-lived daughter products of radon-222 (hereafter called radon) are the main concerns in terms of uranium worker exposures. Their concentrations and physical characteristics such as charge and degree of attachment to aerosols are important parameters in evaluating the degree of hazard they present (for example, see SENES, 1984; NEA, 1983; ICRP, 1981). Since charge and unattached fraction can be affected by electrostatic filtration, typical values of both of these physical characteristics are discussed in the following sections.

The short-lived daughter products of radon-220 (thoron) may also cause significant exposures if their precursor, thorium-232, is present in sufficient concentrations. In Elliot Lake mines, thoron daughter concentrations can approach the radon daughter concentrations (Lowe et al., 1984). Significant thoron levels are not known to occur in Saskatchewan mines.

4.6.2 Attachment/Unattachment To Particles

The unattached fraction of radon daughters has been measured in the range of 2 to 8% at non-diesel areas and less than 2% at areas in which diesel machinery is used (Bigu and Kirk, 1982). In another study of two uranium mines at Elliot Lake, it was observed that the unattached fraction of radon daughters were about 3.7% in non-diesel areas and 2.2% in diesel areas (Busigin et al., 1983). Unattached fractions of lead-212 (Thorium B), the thoron daughter of concern, were about 2.8% and 0.7% in non-diesel and diesel areas respectivley. The results are summarized in Table 4.7.

Table 4.7

UNATTACHED FRACTION MEASUREMENTS FOR TWO ELLIOT LAKE MINES

		Percentage Unattached			
		RaA	RaB	RaC	ThB
Mine No. 1	Average	2.3	0.9	0.5	2.8
	Standard Deviation	1.2	0.5	0.5	2.3
Mine No. 2	Average	1.5	0.7	0.0	0.7
	Standard Deviation	0.5	0.4	0.0	0.6

Notes

- Mine No. 1 measurements were made in a non-diesel (electric) area
- Mine No. 2 measurements were made in a diesel area

Reference

Busigin et al., 1983

The mean unattached fractions of the various radon daughters have also been studied in Norwegian iron ore mines (Stranden and Berteig, 1982). The unattached fraction was found to be highly variable, with the main influencing factor being the aerosol concentration. In most mining situations, the unattached fraction was lower than 0.05, although values higher than 0.3 were measured in areas with very clean air.

While the fraction of unattached radon daughters can be substantial if the particulate concentration is low, in a normal operating mine the particulate concentration is high and the unattached fraction is unlikely to constitute more than a few percent of the total daughter concentration. Recently cleaned air may show a high proportion of unattached daughter activity, but this situation will usually be of short duration, given the abundance of available condensation nuclei in typical mine air (Lindsay et al., 1978). Many investigations have indicated that the aerosol particle concentration is the main factor influencing the unattached fraction (Mercer, 1975, Raghavayya and Jones, 1974, George and Hinchliffe,1972).

4.6.3 Size Range of Attachment

Most radon daughters that are generated by the decay of radon in mine air quickly become attached to aerosol particles in the size range of 0.01 to 0.5 μm (Cooper, 1973). In a study by Bigu and Grenier (1984), radon and thoron daughter activity was preferentially associated with small size particles in the submicron range, with a maximum at about 0.1 μm to 0.35 μm. These results agree with Blanc et al. (1967), Busigin et al. (1978), Jacobi (1963) and Mercer and Stowe (1971).

4.6.5 Charge

Radon and thoron daughters are initially formed in an atomic, positively charged state and rapidly combine with submicron mine aerosols. As mine aerosols are found in positive, negative, and neutral charge states, the

resulting mine atmosphere consists of a complex mixture of charged and neutral particles.

Duport (1978) carried out measurements on the charge state of radioactive aerosols in the CEA laboratory mine. He found that 30% of the radon daughter alpha activity was associated with charged particles and that the ratios of negatively charged to positively charged particles for radium-A, -B and -C were 0.75, 0.6 and 1.6 respectively. Duport also found that the classical equations of atmospheric electricity could be applied to charged radioactive aerosols in a mine.

Based on numerous measurements in an underground uranium mine, Bigu and Grenier (1985) estimated the fraction of charged thoron daughters in an underground mine to be about 65%. Approximately 35% of the thoron daughters associated with mine aerosols in the submicron range were found to be electrically neutral. According to Bigu and Grenier (1985), these data are consistent with radon daughter data collected in a radon/thoron test facility (Bigu, 1984).

5.0 THE EFFICIENCY OF ELECTROSTATIC PRECIPITATORS FOR REMOVING RADIOACTIVE AEROSOLS

This chapter discusses the physical principles underlying the use of electrostatic precipitators to reduce aerosol levels. This theoretical discussion of collection efficiency is followed by short descriptions of actual experience with the use of electrostatic precipitators in underground uranium mines in Canada, France, and the United States.

5.1 Theoretical Efficiency

5.1.1 Particle Collection of Monodispersed and Polydispersed Aerosols

The fundamental physical mechanisms of importance in electrostatic precipitation are electric fields and conduction in the gas phase due to electrons, ions and particles, particle charging, particle transport, and charge transport through collected particulate matter (McDonald et al., 1980). Over the past sixty years, several theories of precipitator efficiency using laminar flow equations have been put forth (for example Deutsch, 1922; Williams and Jackson, 1962; Cooperman, 1971; Leonard et al., 1980).

One of the simplest and most widely cited approaches was developed by Deutsch (1922) for monodispersed aerosols in which it is assumed that particles are uniformly mixed in any cross-section perpendicular to the gas flow due to the gas turbulence. The collection efficiency, n, of a precipitator for a given particle size is given as

$$n = 1 - \exp(-AW/V) \qquad (5.1)$$

where A is the collector plate area (m^2), W is the theoretical migration velocity (m/s) of particles to the collector plate, and V is the air flow rate (m^3/s).

The dependence of the collection efficiency on the quotient A/V implies that

the air flow rate (V) can be increased while maintaining constant efficiency if a corresponding increase in the collection plate area (A) is made. For example, equation 5.1 indicates that air flow rate can be doubled and efficiency maintained by operating two identical electrostatic precipitators in series. Similarly, two precipitators operated in parallel each need only one-half the collection plate area of a single precipitator. This provides flexibility in the design of precipitator configurations.

The theoretical migration velocity (W) was originally derived by Deutsch by balancing the electric field (coulomb) forces on a charged particle against the forces of fluid drag (determined according to Stokes-Cunningham Law). It is possible to calculate W based on information about the external electric field (Cooperman, 1984).

The electric field force (F_1) can be represented by Coulomb's Law as

$$F_1 = q\, E_p \qquad (5.2)$$

where q is the electrostatic charge (coulomb) of the particle and E_p is the strength (V/m) of the collection field.

The following empirical expression developed by Cochet (1961) for predicting the particle charge (q) incorporates field and diffusion charging.

$$q = \left[(1+ \beta/r_p)^2 + 2/(1+\beta/r_p) \right] E_o\, r_p^2 \left[t/(t + 1/(N_o\, e\, K\, \pi))\right] \qquad (5.3)$$

where t = charge time (s)
q = particle charge (C)
E_o = ionizing field strength (V/m)
N_o = ion concentration (ions/m^3)
K = electrostatic mobility of the ions (m^2/V.s)
$\beta = 10^{-5}$ (m, an empirical coefficient)

e = electronic charge (C)

r_p = particle diameter (m).

This relationship has been experimentally verified using industrial electrostatic precipitators (Feldman, 1975).

The fluid drag force (F_2) can be determined according to the Stokes-Cunningham Law of drag

$$F_2 = 6 \pi u r_p W/ (1+a(\lambda/r_p)) \qquad (5.4)$$

where

u = gas viscosity (kg $m^{-1}s^{-1}$)

r_p = particle diameter (m)

W = theoretical migration velocity (m/s)

a = dimensionless parameter (=0.86 for air)

λ = mean free path of ambient gas molecules (m).

By equating F_1 to F_2, the migration velocity, W can be solved as

$$W = (q E_p/(6 \pi u r_p)) \quad (1+a(\lambda/rp)) \qquad (5.5)$$

Equation 5.5 describes the theoretical migration velocity. To accommodate effects not included in the original Deutsch theory (eg. re-entrainment) a variable W_e, the "effective" or "empirical" migration velocity, has been used. This variable is determined from experience with precipitators in similar environments.

Figure 5.1, adapted from Pourprix et al. (1982), shows the effect of particle size diameter and flow velocity on collection efficiency. The data shown on Figure 5.1 were calculated by Pourprix et al. for an Elosta BFSV 4000 precipitator using the Deutsch equation (Equation 5.1). The migration velocity (W) required as input to the Deutsch equation was determined using equation 5.5. In turn the particle charge (q) used in equation 5.5 was

calculated from equation 5.3.

Unfortunately, dust distribution in mine air is not monodispersed. Instead, polydispersed aerosols that contain mineral and hydrocarbon fractions are commonly encountered. To account for non-uniform particle size distributions. integration methods that are based on a known or assumed particle size distribution can be used to calculate precipitation efficiency. By letting $\gamma(x)$ be the size frequency distribution function and $\gamma(x)\,dx$ the fraction of particles having particle size between x and x + dx, the overall efficiency (using equation 5.1) is given by

$$N = 1 - \int_0^{\infty} e^{-(A/V)\,W(x)}\,\gamma(x)\,dx \qquad (5.6)$$

Equation 5.6 can be evaluated analytically in certain cases of practical interest (Calvert and Englund, 1984).

Figure 5.2 adapted from Pourprix et al. (1982) presents the calculated efficiency of a precipitator (an Elosta BFSV 4000 type), as a function of the mean particle diameter and two standard deviations of aerosol dispersion (for a monodispersed aerosol, $\sigma g = 1$; for a polydispersed aerosol, $\sigma g = 5$). The Deutsch equation and a log-normal distribution were used in the above calculations.

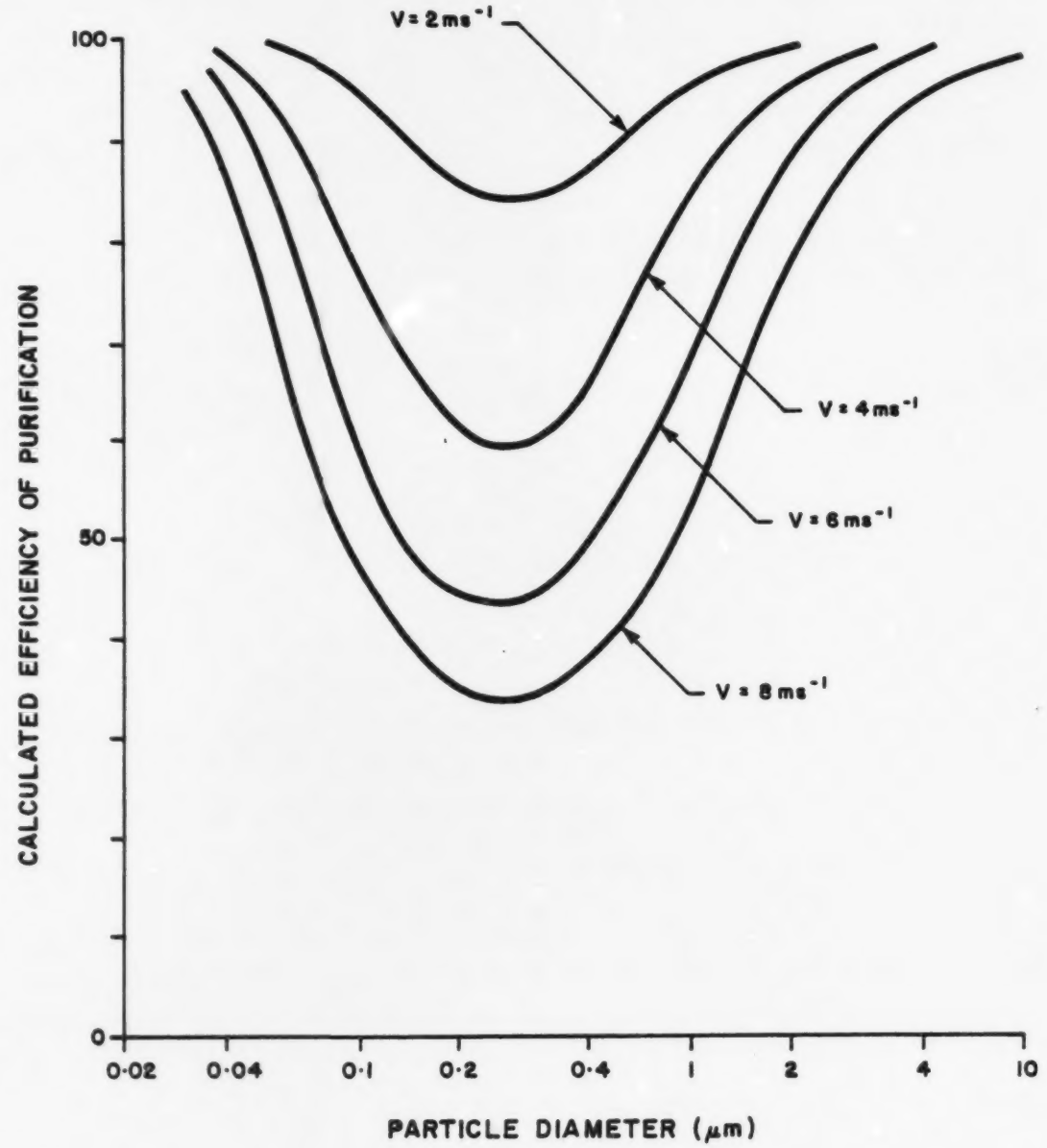
A comparison of Pourprix et al. (1982) calculated values to the results for an underground uranium mine in France has shown that the formula tends to overpredict precipitator efficiency, an example of which is an observed efficiency of 30% and a calculated efficiency of 45% (Pourprix et al., 1982).

5.1.2 Non-ideal Effects

In the past, manufacturers have measured efficiency of full scale precipitators and back calculated an effective migration velocity. This

FIGURE 5·1

EFFICIENCY OF PURIFICATION AS A FUNCTION OF PARTICLE DIAMETER (FOR THE CASE OF MONODISPERSE PARTICLES)



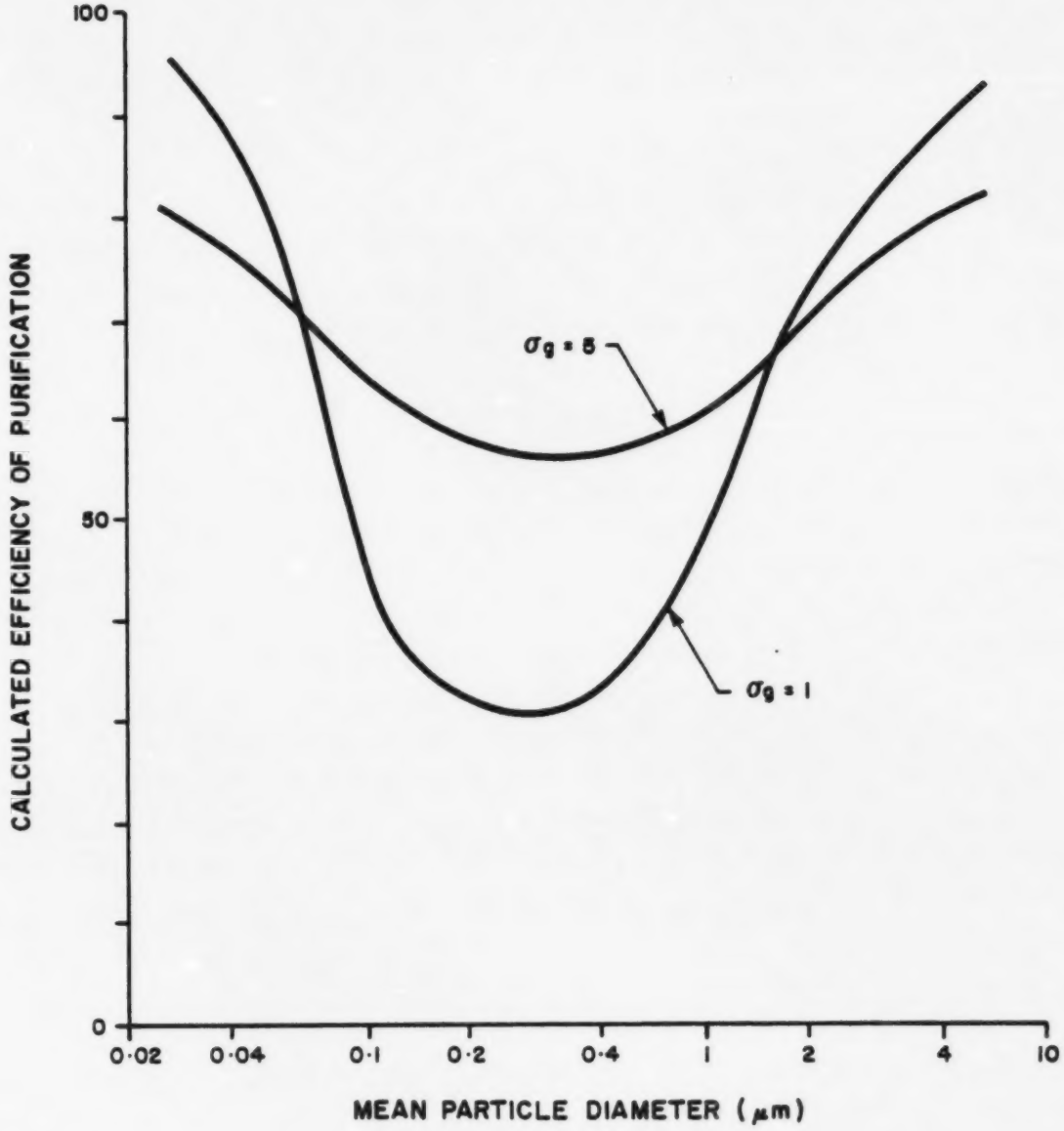
NOTE:

V = FACE VELOCITY

SOURCE: ADAPTED FROM POURPRIX et al, 1982

FIGURE 5·2

INFLUENCE OF PARTICLE DIAMETER ON EFFICIENCY OF PURIFICATION



NOTE :
$V \simeq 9 ms^{-1}$

SOURCE: ADAPTED FROM POURPRIX et al, 1982

procedure worked well for approximating the migration velocity until the advent of new designs of precipitators involving such factors as wide plate spacing, high resisitivity, and taller precipitators. There was no prior experience with the use of these new designs and it became difficult to take into account the effects of non-Deutschian phenomena such as re-entrainment, the effects of diffusion on efficiency, the effects of wide plate spacing, and the particle concentration gradients in the cross-sections prependicular to the gas flow.

It has become possible to account for most non-uniform conditions by extensions of the original theory or the use of empirical factors, but at the price of considerable complication. For many applications the Deutsch formula (equation 5.1) remains the most satisfactory method.

5.1.3 Generic Model for Estimating Electrostatic Precipitator Efficiency

Based on the Deutsch equation, field measurements of some of the key parameters, and the determination of work environment characteristics, it is possible to estimate precipitator efficiency. However, it must be remembered that non-ideal effects can limit the performance of the electrostatic precipitator such that the calculated efficiency could be two to three times higher than can be achieved in practice (White, 1984). Also, the relative performances of different types of precipitators can be compared by estimating their efficiencies in the same theoretical or generic environment. To assist in such a comparison (see Chapter 8), a generic mathematical model was developed that can be used to calculate the purification of an air flow being used to ventilate a work area or a work station.

In the model, the efficiency of the precipitator and the subsequent reduction in potential alpha energy are calculated. The potential alpha energy is from radon and thoron daughters. It is assumed that there is no increase or decrease in the potential alpha energy in the vent tube used to carry air from the precipitator to the workplace (Pourprix et al., 1982), and that the air is used by the worker immediately after purification; hence, there is no influx

of potential alpha energy in the work area. The overall result of these two assumptions is that the reduction in the potential alpha energy received by the worker is the same reduction achieved by the precipitator.

Equation 5.1 is used to calculate the efficiency of the removal of condensation nuclei. It is also used in a separate calculation to calculate the reduction of potential alpha energy. To account for the non-ideal conditions which limit the efficiency of an electrostatic precipitator and the polydispersion of the aerosols, an effective migration velocity (W_e) is used.

The value of the effective migration velocity is based upon field experience and theory (see Section 5.3). As such, the parameter does not represent actual migration velocity, but instead is a semi-empirical parameter (Calvert and Englund, 1984). The value of W_e is determined from the following empirical correlation

$$W_e = F\ E_p\ E_o\ \frac{\frac{6.6 \times 10^{-2}\ A_f}{V}}{\frac{6.6 \times 10^{-2}\ A_f}{V} + 4.02 \times 10^{-3}} \qquad (5.7)$$

where V is the flow rate (m^3/s), E_p the collecting field strength (V/m), E_o the ionizing field strength (V/m), A_f is the face area (m^2) of the precipitator and F is an empirical factor with a value of 4×10^{-7} which was based upon the performance of a two-stage precipitator in a French mine.

In Appendix B, the determination of the effective migration velocity used in the Deutsch equation is shown. Also presented in Appendix B is the computer code of the model.

5.2 Precipitator Performance at Uranium Mines in Canada

One mine tested the performance of a 110 volt precipitator in a lunch room approximately fifteen years ago. The unit operated with a flow rate of 0.333

to 0.38 m^3/s (700-800 cfm) at an efficiency of 75 to 80%. The unit was discontinued because of problems encountered during operating as discussed in Section 5.5.2. The mine currently uses electrostatic precipitators for treating welding fumes in their underground maintenance shops.

No other information on the use of electrosatic precipitators in Canadian uranium mines was identified during this study.

5.3 Precipitator Performance at Uranium Mines in France and Niger

5.3.1 Operating Enviromments

Pilot studies have been conducted in three uranium mines by the Commissariat a l'Energie Atomique (CEA) of France on the efficiency and feasibility of using electrostatic precipitators for the purification of radioactive aerosols. The Chardon and Betoule mines are located in France while the Akouta mine is in Niger.

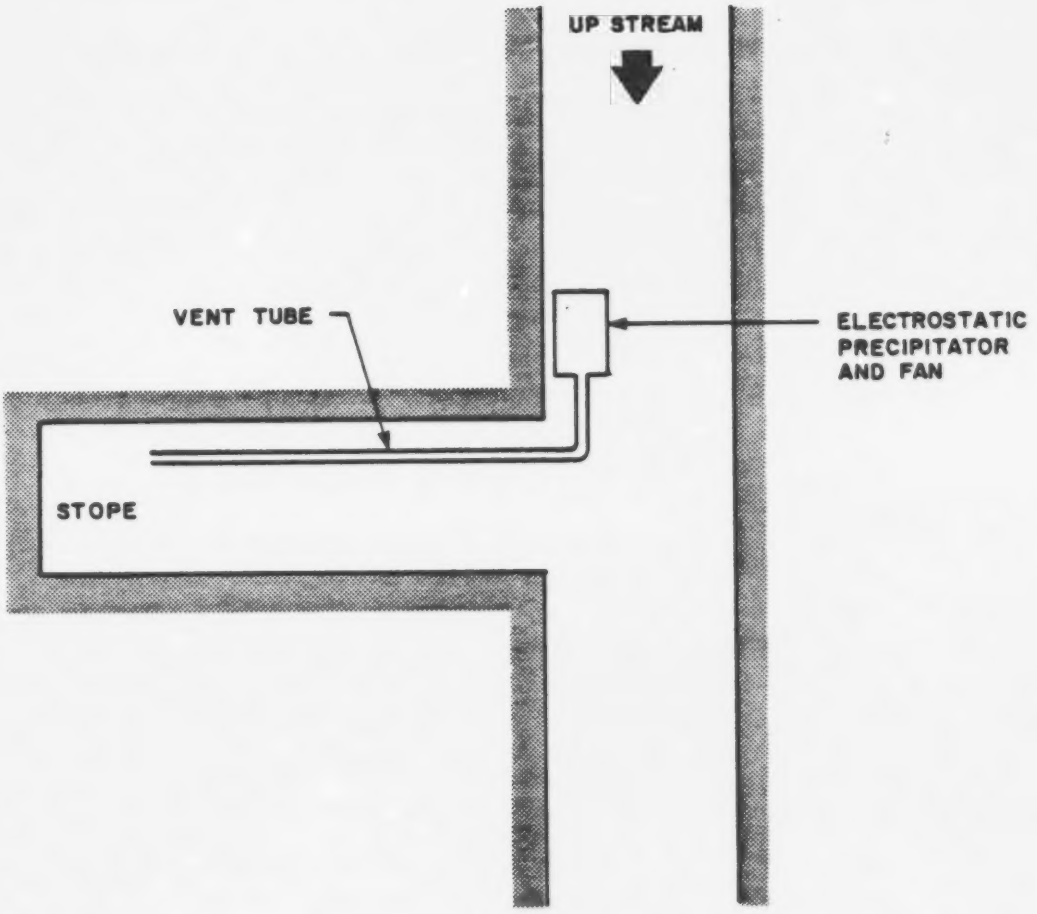
At the two French mines, the electrostatic precipitators were used to purify the auxiliary ventilation air which was directed to a work area as shown in Figure 5.3. The work area in the figure is a stope (Morel et al., 1982).

The configuration of the auxiliary ventilation and flow rates in part of the Akouta mine are shown in Figure 5.4. Auxiliary ventilation is used to ventilate stopes and dead-end workings at a flow of approximately 13.3 m^3/s (28,000 cfm).

Figures 5.5 and 5.6 illustrate the particle size and mass distributions in air upstream and at the stope measured at the Chardon mine. The data indicate that the dust cloud is bimodal, consisting of fumes (particles <1 μm) and dust (particles >1 μm). The majority of the particles in terms of number are less than 1 μm in diameter while in terms of mass, most of the particles are bigger than 1 μm in diameter. The mean diameter of the particles in terms of

FIGURE 5·3

LOCATION OF ELECTROSTATIC PRECIPITATOR IN FRENCH MINES



SOURCE : ADAPTED FROM MOREL et al, 1982

mass was 3.6 μm (Pourprix et al., 1984).

An aerosol concentration of 10^5 nuclei per cm^3 has been reported as being typical of French mines (Pourprix et al., 1984). The aerosol concentration at the Akouta mine has been found to range from 1×10^5 to 4×10^5 nuclei per cm^3 (Morel et al., 1982).

The specific alpha activity of particles versus the particle size in samples collected from the Chardon mine is shown in Figure 5.7. The highest levels of alpha activity are associated with particles of diameters greater than 1 μm which corresponds to the mass of the majority of the particles. Similar data for the other two mines are not available.

In the French mines, the unattached fraction is assumed to be less than 5% (Pourprix et al., 1984). Similar unattached fractions would be expected in Canadian mines. The unattached fraction at the Akouta mine has not been reported.

5.3.2 Equipment Used

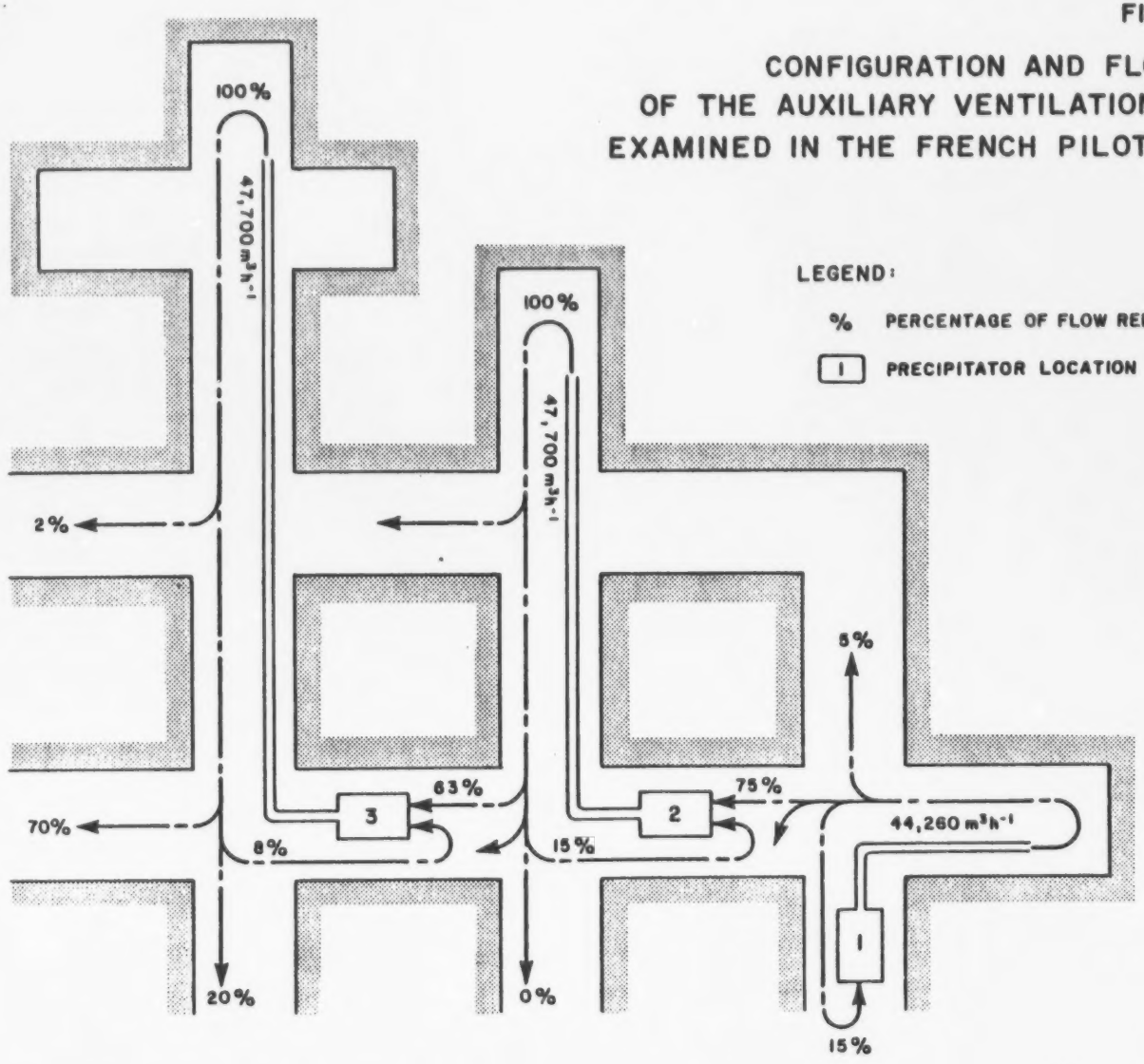
The studies conducted by the CEA used BFSV 4000, BFSV 1000, and BRAUN precipitators. All three are two-stage precipitators with positive coronas. Figure 5.8 illustrates the configurations of precipitators that were employed at each of the mines.

A schematic description of a BSFV 1000 electrostatic precipitator is shown in Figure 5.9. The metallic wire grills at the entrance and exit of the precipitator provide physical protection; the entrance grill also acts as a prefilter. In the first stage of precipitation, the corona discharge occurs. A voltage of 11000 volts is used. In the second stage, the voltage across the parallel plates is +5500 volts. The BFSV 4000 and BRAUN precipitators have the same general design.

Three sets of experiments were conducted: an initial feasibility study using

FIGURE 5·4

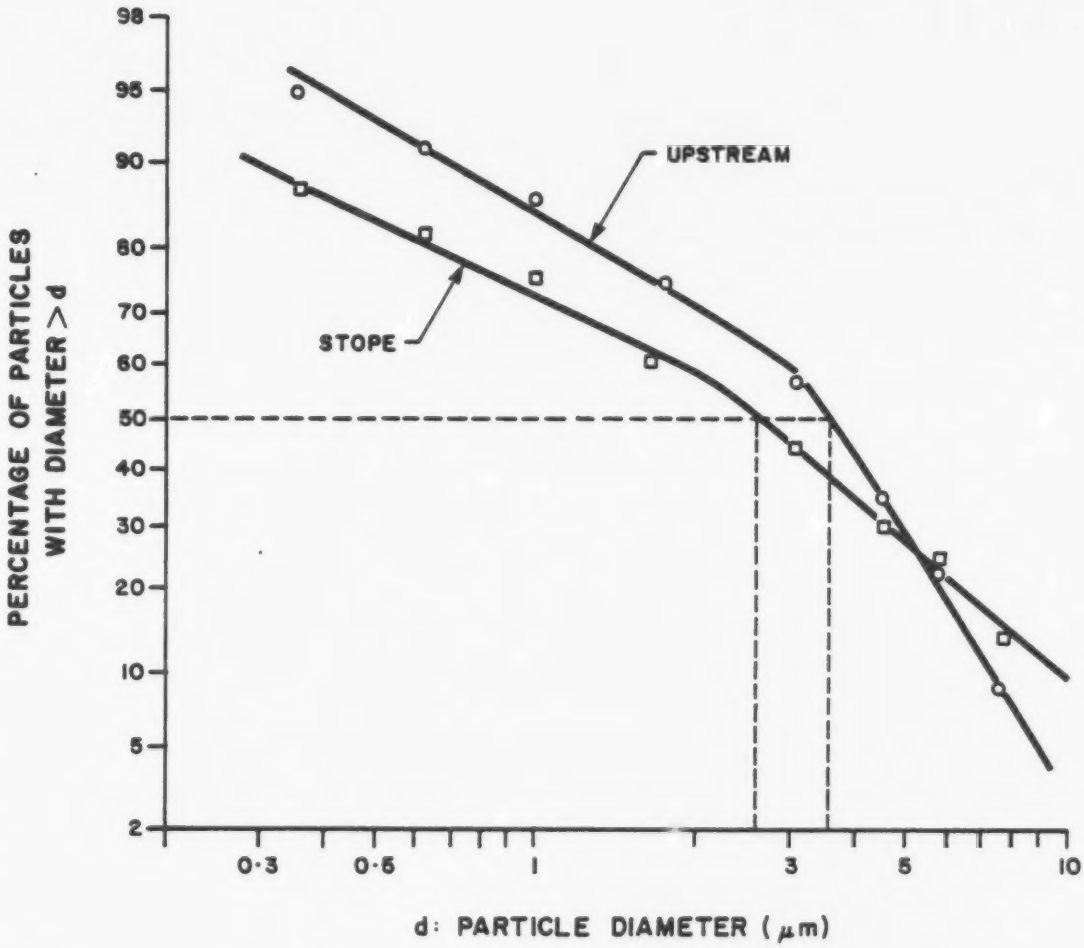
CONFIGURATION AND FLOW RATES OF THE AUXILIARY VENTILATION SYSTEM EXAMINED IN THE FRENCH PILOT STUDIES



SOURCE: ADAPTED FROM MOREL et al, 1982

FIGURE 5·5

DISTRIBUTION OF PARTICLE SIZE UPSTREAM OF THE PRECIPITATOR AND AT THE HEAD OF THE STOPE



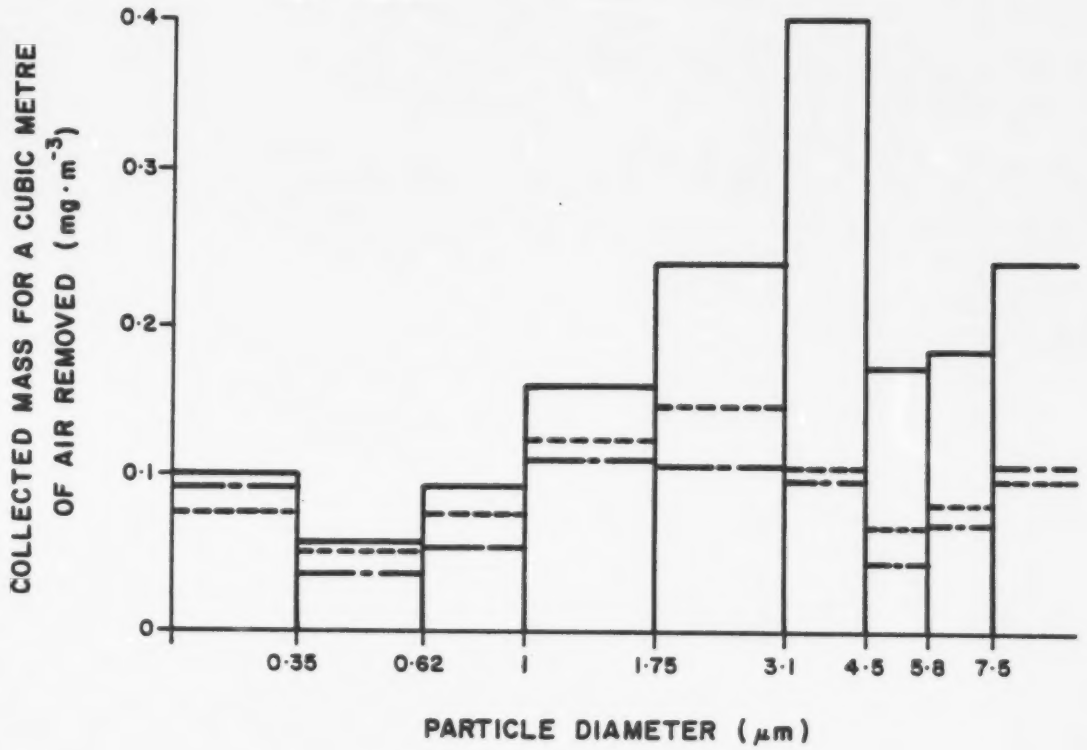
NOTE:

RESULTS ARE FROM THE COGEMA MINE

SOURCE: ADAPTED FROM MOREL et al, 1982

FIGURE 5·6

RESULTS OBTAINED WITH AN ANDERSON IMPACTOR



LEGEND:

——— UPSTREAM

—·—·— STOPE

- - - - - - RETURN AIR

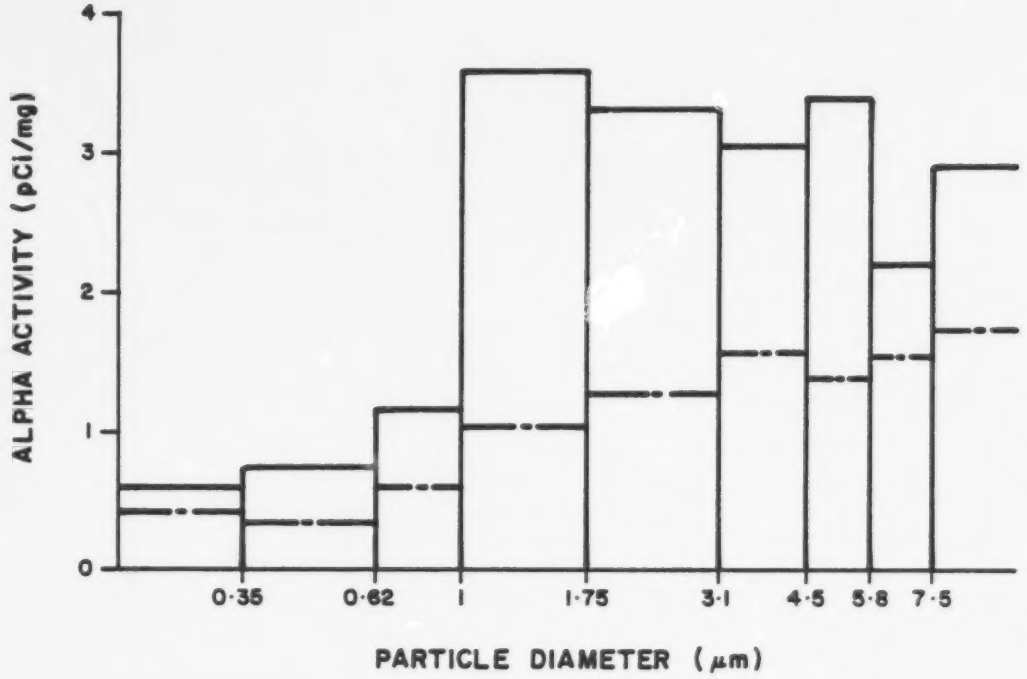
NOTE:

RESULTS FROM THE CHARDON MINE

SOURCE: ADAPTED FROM MOREL et al, 1982

FIGURE 5·7

EFFICIENCY OF ALPHA ACTIVITY REMOVAL vs. PARTICLE DIAMETER



LEGEND:

——— UPSTREAM

—·— STOPE

NOTE:

SAMPLES WERE NOT TAKEN SIMULTANEOUSLY

SOURCE: ADAPTED FROM MOREL et al, 1982

the BRAUN at a nominal air flow rate of 0.017 m^3/s on confined air; an intermediate level experiment using a BSFV 1000, at a nominal flow of 0.28 m^3/s; and a full size pilot study using a parallel configuration of BSFV 4000 at a nominal flow of 1.11 m^3/s. The latter two experiments had four precipitators located at the end of a vent tube with a diameter of 0.6 m and 4.17 m^3/s flow (Figure 5.8).

5.3.3 Results

Based on the results of the CEA studies, the experimental efficiency of a single electrostatic precipitator as a function of flow was determined and is shown in Figure 5.10. The efficiency is based upon the potential alpha energy upstream and downstream of the electrostatic precipitator. In Figure 5.11. the potential alpha energy is shown as a function of the sample location for three different combinations of electrostatic precipitators in the Chardon mine. The figure also shows that no loss or appearance of alpha energy occured in the vent tube.

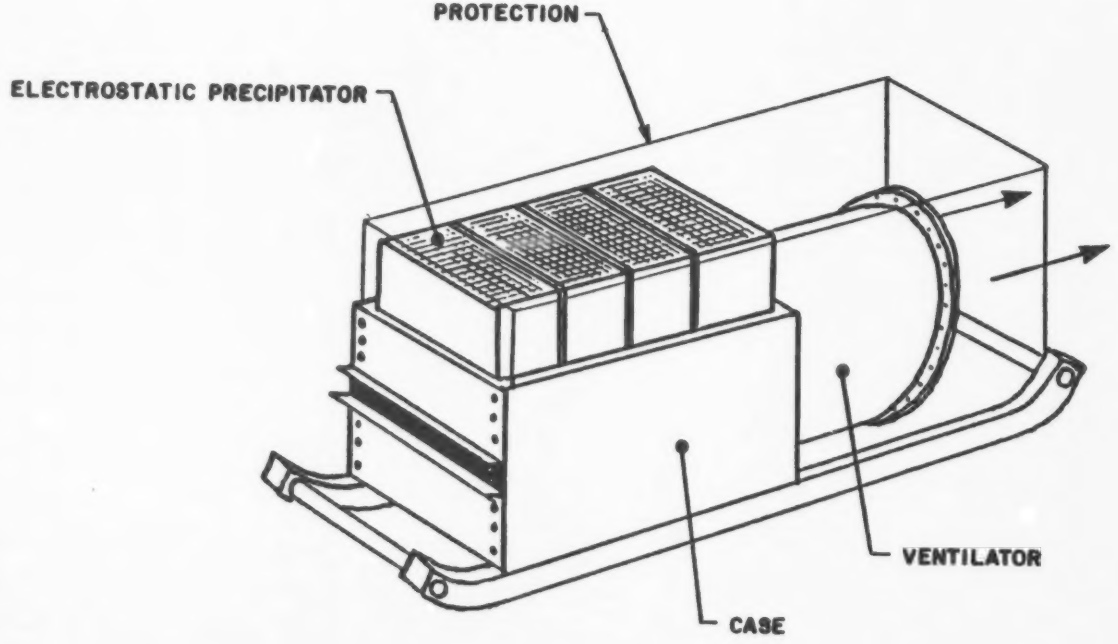
In Table 5.1, flow rates, velocities and efficiencies for three combinations of electrostatic precipitators are presented. In terms of efficiency, the greater the number of precipitators, the higher the efficiency. A much larger efficiency improvement occurred when the number of precipitators was increased from one to two than when increased from two to three.

The particle size range in which the precipitator achieved the highest efficiency, in terms of mass removal, was for particles greater than 1 μm in diameter (see Figure 5.6). This also corresponds to the particle sizes which have the highest alpha activity when expressed in pCi per unit mass, as shown in Figure 5.7.

The removal efficiency of the unattached fraction was not measured in the CEA studies. Pourprix *et al.* (1984) have suggested that the unattached fraction is completely removed by an electrostatic precipitator.

FIGURE 5·8

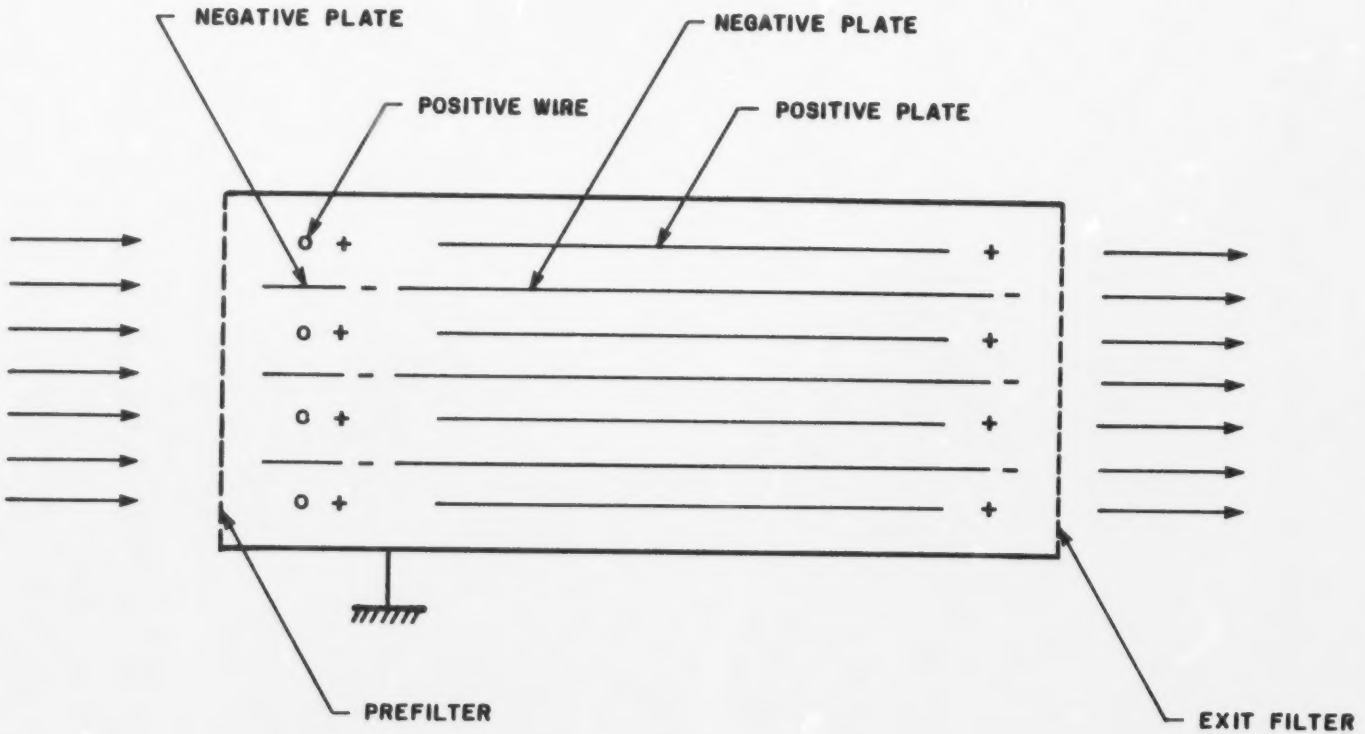
CONFIGURATION OF ELECTROSTATIC PRECIPITATORS



SOURCE: MOREL et al, 1982

FIGURE 5-9

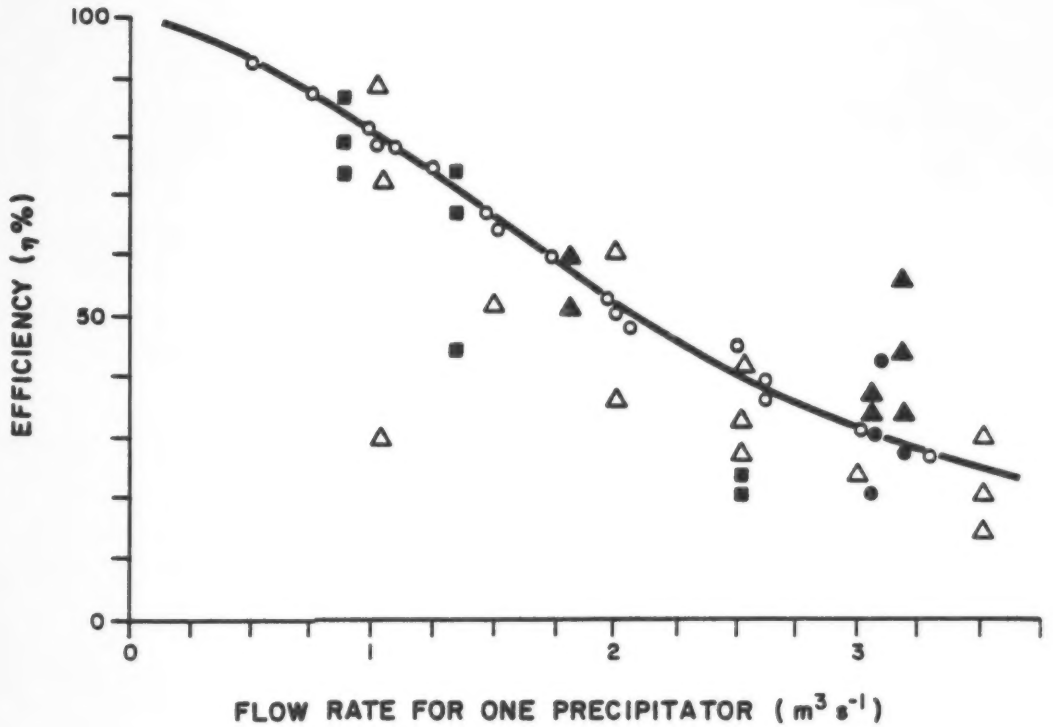
SCHEMATIC OF A BFSV 1000
ELECTROSTATIC PRECIPITATOR



SOURCE: ADAPTED FROM MOREL et al, 1982

FIGURE 5·10

EFFICIENCY OF PURIFICATION AS A FUNCTION OF FLOW RATE (ELOSTA BFSV 4000 ELECTROSTATIC PRECIPITATOR)



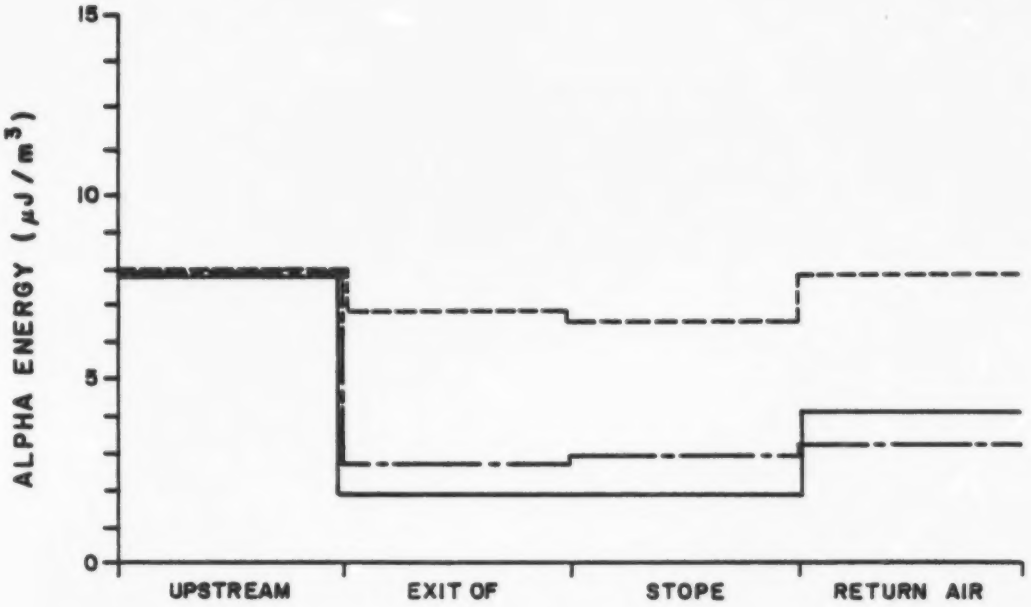
LEGEND:

- ○ CONDENSATION NUCLEI (BETOULE)
- △ E_a TOTAL POTENTIAL (BETOULE)
- ■ E_a TOTAL POTENTIAL (CHARDON)
- ▲ E_a TOTAL POTENTIAL (AKOUTA)
- ● CONDENSATION NUCLEI (AKOUTA)

SOURCE: ADAPTED FROM POURIX et al, 1982

FIGURE 5-11

NORMALIZED EVOLUTION OF ALPHA ENERGY AS A FUNCTION OF THE NUMBER OF PRECIPITATORS



LEGEND:

- ONE PRECIPITATOR
- TWO PRECIPITATORS
- THREE PRECIPITATORS

SOURCE: ADAPTED FROM MOREL *et al*, 1982

Table 5.1

PRECIPITATOR EFFICIENCY VERSUS AIR FLOW, VELOCITY AND PRECIPITATOR CONFIGURATION*

Efficiency (%)	Flow (m^3/s)	Velocity ** (m/s)	Configuration
77.0	2.66	2.7	3 precipitators
60.7	2.63	4.0	2 precipitators
23.5	2.49	7.5	1 precipitator

Notes

* This study was conducted in the Chardon uranium mine, France.

** The cross-sectional area of the BSFV 4000 is 0.333 m^2.

Reference

Morel et al., 1982

5.4 Precipitator Performance at Uranium Mines in the United States

5.4.1 Operating Environments

In the early seventies, Union Carbide used electrostatic precipitators in mines in the Uravan Mineral Belt to remove radon daughter products from mine air (Beverly, 1985). Approximately 50 precipitators were purchased and used for six to eight years (Slade, 1985).

The Uravan Mineral Belt is a uranium-vanandium mining district located in southwestern Colorado and southeastern Utah. Mines in the district have experienced difficulties in providing adequate ventilation radon daughter control due to several factors: the ore deposits are irregularly shaped and difficult to delineate, the irregular configuration of mine workings produces many areas of stagnant air, and old workings with small airways that are often caved have been reactivated (Swindle, not dated).

Since the orebodies are so discontinuous and unpredictable, the farthest limits of ore in a mine can not be determined. This precludes the use of a retreating system of mining that would permit contaminated air to be exhausted through mined-out workings and hence reduce the amount of ventilation required. As a result, it is usually necessary to ventilate extensively mined-out workings to maintain haulageways and ventilation airways that serve the areas being mined. The mined-out workings are often major sources of radon daughters (Swindle, not dated).

The irregular configurations of the mines peripheral stope areas are difficult to ventilate because they are partly or completely by-passed by the primary air currents. Ventilation to these areas is accomplished by the installation of numerous booster fans, auxiliary fans, and air diversion stopes. The net result is that a slow movement of air through a work space may result in air stagnation. This slow movement, especially through a stope area, can cause an increase in the radon daughter contamination farther downstream in the ventilation circuit (Swindle, not dated).

Many of the old workings in these mines were worked when the ventilation requirements were far less stringent than they are today. As a result, the ventilation holes and airways are often too small to provide the necessary ventilation. In some of the older areas, haulageways were driven in mudstone beneath the ore horizons that have since caved.

No information is available in the literature on the operating environment in terms of dust concentrations or physical characteristics or humidity and temperature.

In a study by George et al. (1975) of four uranium mines located near Grants, New Mexico, the activity median diameter of radon daughters ranged from 0.09 µm to 0.3 µm with a mean value of 0.17µm. Geometric standard deviations were in the range of 1.3 to 4 with a mean value of 2.7. The uncombined fraction of radon daughters ranged from 0.004 to 0.16 with a mean value of 0.04. A round-jet cascade impactor was used for these measurements. The effective cut-off diameter of the last stage was 0.11 µm.

5.4.2 Equipment Used

At the Deremo Snyder Mine in Colorado, electrostatic preciptators (the Westinghouse Model PM Precipitron) were used for several years (Swindle, 1971). This type of precipitator is no longer produced.

The PM Precipitron had a solid-state, high-voltage, power pack mounted on each cell. Each cell comprised one precipitator that was 0.9 m (3 ft) wide and 0.6 m (2 ft) high. The collectors were constructed of thin aluminum plates and the discharge electrodes were tungsten wires, 0.15 mm (0.006 in) in diameter (Swindle, no date).

The precipitators were operated at a face velocity of approximately 1.5 m/s (300 cfm) to achieve a working level reduction efficiency of about 90% (Swindle, no date). The cells were individually mounted in steel housings that could be stacked and bolted together in any configuration. Figure 5.12

shows a typical configuration of a PM Precipitron.

5.4.3 Results

Efficiencies measured in terms of the reduction in working levels were found to vary from approximately 65 to 95 % depending on the air velocity. Figure 5.13 shows the relationship between efficiency and front face velocity that was observed. The figure also shows the manufacturer's rated efficiency.

5.5 Operational Problems

5.5.1 General Problems

The primary cause of operational breakdown in electrostatic precipitators is discharge electrode failure. Other causes (according to the rate at which they occur) are rapper malfunctions, insulator failures, shorts caused by dust buildup, hopper plugging, and transformer-rectifier failures (U.S. EPA, 1978).

Discharge electrodes, also called ionizer wires, frequently require servicing even under the best conditions of maintenance and operation.

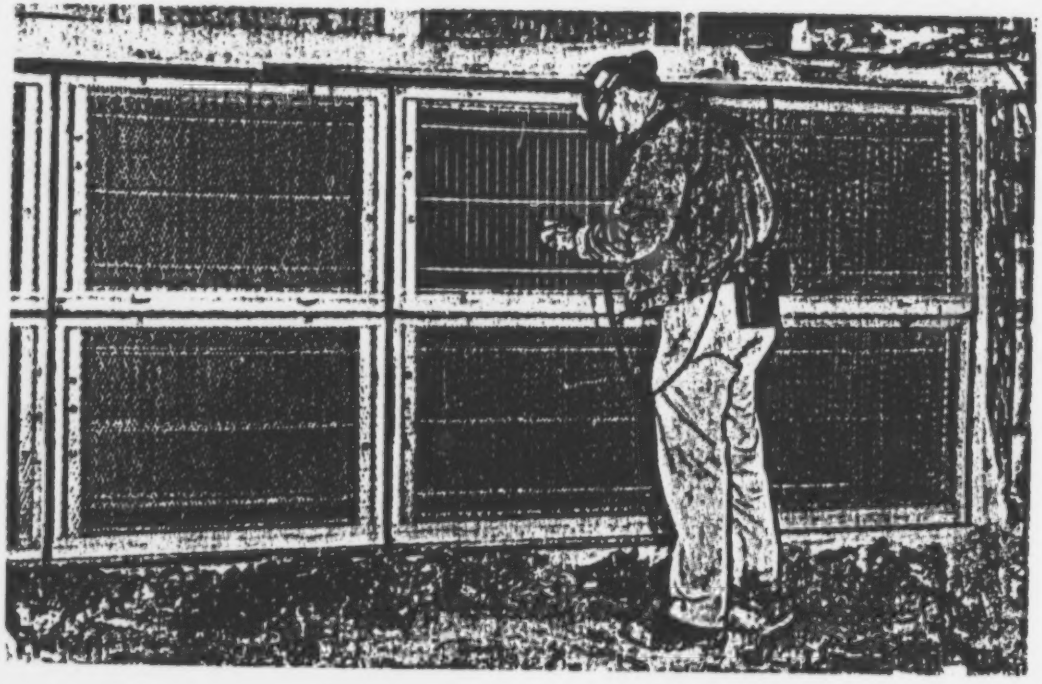
Besides electrical and rapping problems, precipitators can develop problems involving gas flow and mechanical systems. Uneven gas flow can cause erosion of the collection plates, dust fallout and accumulation on turning vanes and ductwork (U.S. EPA, 1978).

5.5.2 Problems Experienced in Canada

During the testing of a precipitator in an underground mine, pitting and sparking were observed. Pitting, a form of corrosion, was believed to occur as a result of the plates not being made of stainless steel. All of the manufactured precipitators which were reviewed in this study have stainless steel plates.

FIGURE 5-12

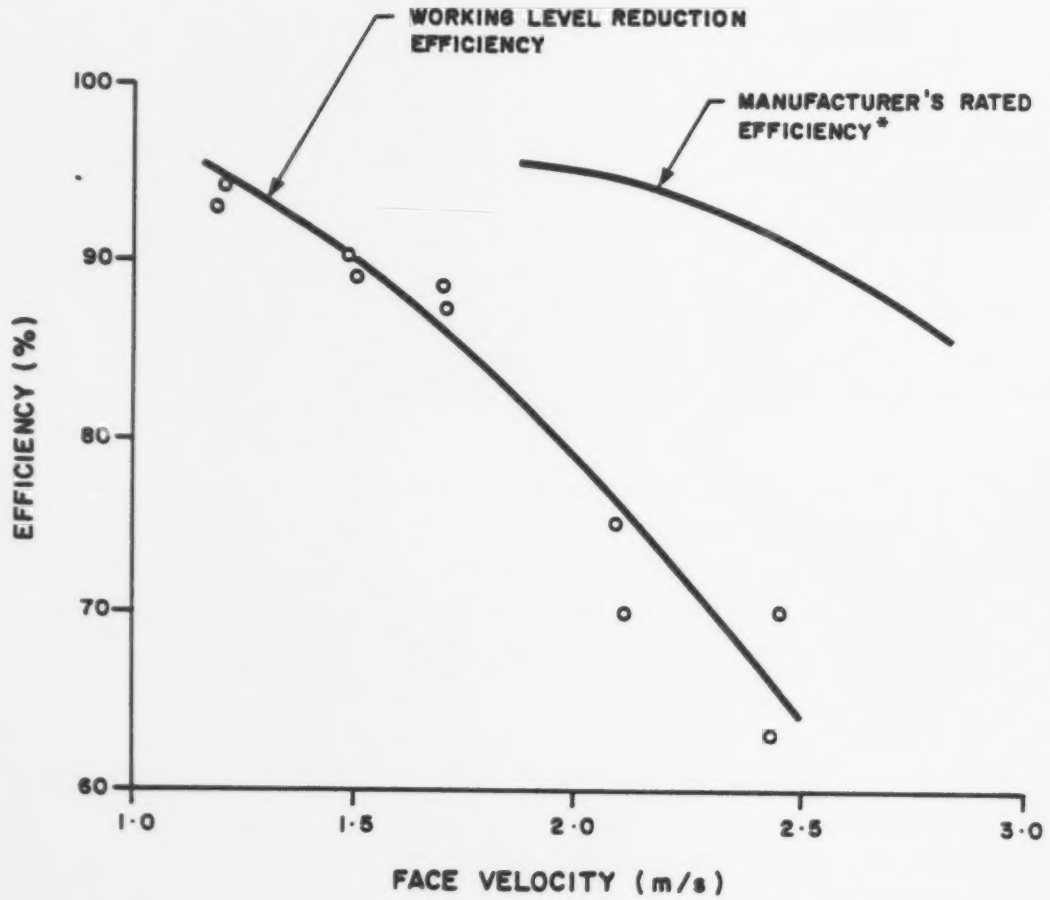
UNDERGROUND ELECTRONIC AIR CLEANER INSTALLATION CONSISTING OF WESTINGHOUSE MODEL PM PRECIPITRON CELLS INSTALLED IN SPECIALLY FABRICATED STEEL HOUSINGS



SOURCE: SWINDLE, 1971

FIGURE 5·13

EFFECT OF AIR VELOCITY ON EFFICIENCY OF PURIFICATION FOR A WESTINGHOUSE MODEL PM PRECIPITRON



NOTE:

* NBS DUST SPOT TEST USING ATMOSPHERIC DUST

SOURCE: ADAPTED FROM SWINDLE, 1971

The sparking problem resulted under conditions of high humidity. To overcome the problem, a lower voltage may be employed. Unfortunately, a lower voltage also results in a lower collection efficiency.

5.5.3 Problems Experienced in France and Niger

A major problem experienced in the CEA studies was adapting the precipitators so that they did not physically obstruct access in passageways and work stations. In an attempt to overcome this problem, the precipitators were placed in a parallel configuration on a sled (see Figure 5.8). The sled allowed the equipment to be easily transported to different locations. Even with the parallel configuration, the precipitators obstructed passageways.

Methods that can be used to reduce the drift space occupied by the precipitators are: series configuration, reduced precipitator size, and enlargement of the drift at a particular location.

A second problem encountered during the CEA studies was the damaging of the power packs by sparking. This problem has also been experienced in the Witwatersrand gold mine where electrostatic precipitators have been used from time to time over the last 25 years to remove silica dust from the mine air. The CEA overcame the problem by providing the power packs with current limiters (Pourprix et al., 1984).

A third problem was the difficulty of relocating the equipment from work area to work area. Precipitators and fans were assembled together and placed on sleds but the overall sled length did not all allow for sharp turns and made other manoeuvres difficult. The proposed solution to this problem was that the precipitators and exhaust fan be assembled as two separate units and only joined at the location of use (Morel et al., 1982).

At the Akouta mine, water leaking from the ceiling onto the precipitators created problems in starting the machine at low voltage. It is probable that

the water caused short circuits.

Table 5.2 presents a summary of the problems observed during the CEA studies.

5.5.4 Problems Experienced in the United States

At the mines in the Uravan Belt, the precipitators required weekly cleaning by hand. The suspected reason for the difficulty in cleaning the precipitators was the presence of diesel exhaust and a high humidity which caused the plates to rapidly develop a coating that was not easily removed (Beverly, 1985).

To avoid a coat from forming, an automatic self-cleaning (water-wash) electrostatic precipitator can be employed. The cleaning system should be a high pressure nozzle spray type and use a detergent which has been tested against diesel film buildup. The automated system enables a higher frequency of wash cycle to be used in an attempt to avoid the problem before it happens.

A second problem encountered with the Westinghouse precipitators was the frequent breakage of ionizer wires. Tungsten wires of diameter 0.15 mm were used as the ionizer wires. Most electrostatic precipitators manufactured today have ionizer wires of 0.20 to 0.25 mm diameter.

The third problem encountered in the U.S. mines was electrical short-circuiting in the electronic part of the equipment. The short circuits were caused by condensate, formed under the high humidity conditions, that would accumulate inside the equipment. The collection of condensate inside the electronic part of the precipitators can be avoided if properly sealed precipitators are used. In recent communication with manufacturers, the sealing of the precipitator for use in conditions of high relative humidity was not seen as a problem.

Table 5.2 summarizes the problems observed at the U.S. mines.

Table 5.2

PROBLEMS OBSERVED WITH ELECTROSTATIC PRECIPITATORS DURING THEIR OPERATION IN UNDERGROUND URANIUM MINES

Mine Location	Problem	Cause	Possible Solution
Canada	pitting of plates	collection plates not made of stainless steel	use of stainless steel collection plates
	sparking	high humidity	use lower voltage in the collecting section and current limiters
U.S.	frequent cleaning	diesel exhaust and high humidity	automatic self-cleaning equipment
	ionizer wire breakage	wires too thin	thicker wires
	electronic short circuiting	high humidity	seal equipment
France and Niger	blockage of drifts and relocation of equipment	precipitators too large	reduce precipitator size, arrange in parallel or series, or enlarge the drifts
	sparking	high humidity	use lower voltage in the collecting section and current limiters
	starting difficulties	water leakage	seal equipment

6.0 REVIEW OF AVAILABLE ELECTROSTATIC PRECIPITATORS

6.1 Overview

This chapter contains the results of a two part survey of manufacturers of electrostatic precipitators. For the first part of the survey, the manufacturers who were listed in the commercial directories as producing ventilation-type, two-stage electrostatic precipitators were contacted by mail or phone. The criterion of a two-stage device greatly limited the number of manufacturers to be contacted, since most produce single-stage electrostatic precipitators for treating industrial flue gases. For the second part of the survey, more detailed specifications and costing information was requested from the manufacturers who had replied to the mail-out.

Based on the survey response it appears there is a lack of practical experience among precipitator manufacturers for the application of precipitators in underground mines.

Appendix A contains a list of the companies that were contacted and the companies that replied to the request.

6.2 Available Equipment and Specification

In Table 6.1 the specifications for the different types of two-stage electrostatic precipitators are listed. The specifications, dimensions, and weight are for a precipitator cell. The velocity, flow rate, collection area and corresponding efficiency for a basic modular unit are shown in Table 6.2. The specifications for control units, including casing, are shown in Table 6.3. A control unit consists of several precipitator cells in series or parallel. The Beltrans Associates precipitator is of a tubular design. In the tubular design, the paralled plates comprising the collection section have been replaced by an "egg crate" grid of electrically grounded rectangular tubes.

Table 6.1

MANUFACTURERS' SPECIFICATIONS
(SINGLE CELLS)

Specifications	Manufacturer: N.R. Murphy	Davis Energy Systems	AAF-Canada	Beltran Association
TYPE	AQUATRON	IP	ECU	TUBULAR
Dimensions:				
Height (m)	0.61	0.46	0.41	4.57
Width (m)	0.46	0.41	0.61	0.91
Depth (m)	0.46	0.71	0.25	0.91
Weight (kg)	29.1	20.4	20 *	1600*
Plates:				
Gross face area (m^2)	0.28	0.19	0.37	3.54
Spacing (cm)	0.775	0.95	0.757	N.A.
Depth (cm)	33.0	45.7	25.4	0.91
Collector surface (m^2)	8.5	5.8	5.0	91.4
Thickness pos. (cm)	0.81	0.76	0.051	0.16
neg. (cm)	0.81	0.76	0.107	0.16
Ionizer:				
Wire diameter (cm)	0.025	0.043	0.020	0.16**
Wire/plate spacing (cm)	2.57	1.91	3.29	N.A.
Insulator diameter (cm)	7.62	3.18	7.94	N.A.
Operating:				
Current (ma)	2.4	1.42	1.2	15-30
Voltage, Ionizer (KV)	14.0	10.0	14.0	20-25
Collector (KV)	7.0	6.0	6.8	20-25
Collecting field (KV/m)	903	632	898	984
Ionizer charge (KV/m)	545	523	426	656

Notes

* Approximate value
** Diameter of the needle
N.A. Not Available

Table 6.2

MANUFACTURERS' SPECIFICATIONS
(TWO CELLS)

Specifications	Manufacturer		
	N.R. Murphy	Davis Energy Systems	AAF-Canada
TYPE	AQUATRON	IP	ECU
Efficiency (%)	95 *	85-90 **	95 *
Flow (m^3/s)	1.42-1.77	0.94	1.85
Velocity (m/s)	2.53-2.39	2.47	1.8
Face area (m^2)	0.56-0.74	0.38	1.03

Notes

* Ashrae efficiency
** Dop efficiency

Table 6.3

MANUFACTURERS' SPECIFICATIONS
(CONTROL UNITS)

Specifications	Manufacturer: N.R. Murphy	Davis Energy Systems	AAF-Canada	Beltran Association
TYPE	AQUATRON 15-4-3-2	IP 14/2	ECU 10-55	TUBULAR 1
Number cells	8	14	16	1
Cell configuration (high x wide x long)	4x2x1	7x2x1	4x2x2	1
Efficiency (%)	95 *	85-90 **	95 *	99.5**
Flow (m^3/s)	5.66	6.61	5.45	1.42
Velocity (m/s)	2.54	2.50	2.1	3.54
Cell face area (m^2)	2.23	2.64	2.6	91.4
Collection area (m^2)	68.0	81.1	80.0	4.57
Height (m)	2.5	1.12	1.83	0.91
Width (m)	0.97	3.25	2.03	0.91
Depth (m)	1.19	0.71	1.77	1600+
Weight (kg)	488	1020	1112	

Notes

* Ashrae efficiency
** Dop efficiency
\+ Approximate value

The control units presented in Table 6.3 have flow rates ranging from 5.6 to 7.0 m^3/s (12000-15000 cfm) with a corresponding 95% efficiency. These specifications represent approximately 60 to 70% efficiency at a flow rate of 14 to 23 m^3/s (30000-50000 cfm).

The flow rate range of 14 to 23 m^3/s is representative of the auxiliary ventilation flows in Canadian uranium mines. The 60 to 70% efficiency range is seen as a reasonable level of reduction since the levels in the Canadian uranium mines are already low. Higher efficiency would increase the cost factor exponentially.

6.3 Quotations

Quotations have been received for the previously described control units (Table 6.3). The quotations, listed in Table 6.4, are for the net price of the unit, either primary or auxiliary, and assorted accessories such as an automatic wash section.

Table 6.4

MANUFACTURERS' PRICE QUOTATIONS

Company	Equipment	Type	Net Price (thousands of dollars)
N.R. Murphy	"Aquatron" Model 15-4-3-2 (includes wash section)	A+B	17.66
Davis Energy Systems	"IP" Model #IP-14/2	A	14.0
	Automatic Wash Section using detergent and water	B	4.7
		A+B	18./
AAF-Canada	ECU Model #10-55	A	17.1
	Washer and Controls	B	7.2
		A+B	24.3
Beltran Assoc. Inc.	tubular controls	A	52**
		B	2**
		A+B	54

Notes

* Net price does not include provincial or federal sales taxes or fan
** Approximate values

A Basic electrostatic precipitator
B Auxiliary equipment

7. COST OF USING ELECTROSTATIC PRECIPITATORS IN UNDERGROUND CANADIAN URANIUM MINES

The costs associated with the use of electrostatic precipitators in an underground mine are capital costs and annual operating costs.

7.1 Capital Costs

The capital costs may be divided into three categories:

i) equipment purchase
ii) equipment installation
iii) engineering and testing

These categories may be further subdivided into more descriptive subunits as shown in Table 7.1.

The equipment purchase cost consists not only of the direct costs for the purchase of the actual electrostatic precipitator and the auxiliary attachments such as a washer section, but also includes the cost of instruments, controls, taxes and freight. Some manufacturers, however, include the cost of instruments and controls in the purchase cost.

The cost of a fan subsystem and ductwork has not been included in the auxiliary equipment since it has been assumed that the electrostatic precipitators will be used to reduce the radioactive aerosol loading to a dead-end work area which is already being ventilated.

From Table 7.1, the equipment purchase price, X, of an electrostatic precipitator can be expressed by the following operation:

$$X = 1.22\ (A + B) \qquad (7.1)$$

where A is the direct cost for purchase of the electrostatic precipitator and B is the cost for the auxiliary attachments.

Table 7.1

INSTALLED COST IN AN UNDERGROUND MINE

Direct Costs	Cost
Equipment Purchase:	
- Primary	A
- Auxiliary	B
- Instruments and Controls	0.10 (A + B)
- Taxes (assumed Ontario rate)	0.07 (A + B)
- Freight	0.05 (A + B)
Base Price	X (total of above)
Equipment Installation:	
- Platform, sled and/or supports	0.06 X
- Handling and assembly	0.50 X
- Site preparation	0.20 X
- Electrical hook-up	0.08 X
- Piping hook-up (washer)	0.01 X
	0.85 X
Engineering and Testing:	
- Engineering and Supervision	0.20 X
- Start-up	0.01 X
- Performance test	0.01 X
	0.22 X

Reference

Calvert and Englund (1984).

The major portion of the installation cost of an electrostatic precipitator in an underground mine, as shown in Table 7.1, is for handling and assembly. At approximately 50% of the equipment purchase price X, this portion includes the transportation of the precipitator sections from the surface to the underground location, the assembly of the various components and the connection of the electrostatic precipitator to the fan and ductwork. Other installation costs include the construction of supports/platform and/or sled, the electrical and piping hookup and the site preparation. It should be noted that the site preparation may also include the enlargement of a drift at a particular location although this cost is not included in the present analysis. The overall direct installation cost (exclusive of mine specific costs) as shown in Table 7.1 is 0.85 X.

The engineering and testing costs associated with the installation of an electrostatic precipitator are engineering and supervision, start-up and performance testing. This indirect installation cost is approximately 0.22 X.

Based on the three components described above, the Total Installed Cost (TIC) of an electrostatic precipitator in an underground mine can be expressed as:

$$\begin{aligned} TIC &= X + 0.85X + 0.22X \\ &= 2.07X \end{aligned} \qquad (7.2)$$

A listing of the TIC values for the various precipitators is presented in Table 7.2. Control unit is in reference to a group of precipitators placed in one housing.

7.2 Annual Operating Costs

The Annual Operating Cost (AOC) in dollars per year is comprised of direct (D), and indirect (I) operating costs shown in Table 7.3.

$$AOC = D + I \qquad (7.3)$$

Table 7.2

TOTAL INSTALLED COST*

Control Unit	Flow (m^3/s)	Base Price (X) (x $1000)	Total Installed Cost (TIC) (x $1000)
Aquatron 15-4-3-2	5.66**	21.55	44.61
IP - 14/2	6.61†	22.81	47.22
ECU -10-55	5.45**	29.65	61.38
Tabular	1.42††	54.0	111.78

Notes

* Installed cost for the control units described in Table 6.2

** Flow rate for a 95% ASHRAE efficiency

† Flow rate for a 85-90% DOP efficiency

†† Flow rate for a 99.5 DOP efficiency

Table 7.3

ANNUAL OPERATING COSTS*

Direct Operating Costs (D)

1.	Operating labour	$2875
2.	Operating materials	100
3.	Maintenance labour	5250
4.	Replacement materials	400
5.	Waste treatment and disposal	0
		$8625

Indirect Operating Costs (I)

6.	Overhead**	0
7.	Insurance and administration	0.03 (A + B)
8.	Amortized Capital Cost	$\frac{0.18\ (TIC)}{0.03\ (A + B)+0.18\ (TIC)}$

Notes

* One control unit in continuous operation during 2 shifts/day
** Included in base labour rates used to calculate #1 and #3

Reference

Adapted from Calvert, S. and Englund, M., Handbook of Air Pollution Technology, (1984).

The AOC is an appropriate parameter on which to base comparisons of competing control systems since it accounts for both the investment and the expenses necessary to operate and maintain the control system (Calvert and Englund, 1984).

7.2.1 Direct Operating Cost

The direct operating cost as shown in Table 7.3 consists of operating labor, operating materials, maintenance, replacement materials, utilities, and waste treatment and disposal. The annual cost is estimated to be $8,625 per unit based on the following assumptions:

i) Operating Labour

The operating labor requirement is a function of the size, complexity, level of automation and operating mode (batch or continuous) of the control unit selected. The electrostatic precipitator control units listed in Table 7.1 all have automated wash sections and operate on a continuous mode.

For the Operating Labour Cost component, OLC ($/yr), the following expression was used

$$OLC = WR \times 1.15 \times t \times d \qquad (7.4)$$

where WR is the Wage Rate of an operator ($/hr), t is the estimated labour hours per three shifts and d is the number of days per year. labour rates include payroll and plant overhead). The factor 1.15 accounts for the supervisory labour requirement at 15% of the base labour rate. In the calculations, WR is $20/hr, t is a half hour and d is 250. The number of days was determined from 5 days a week, 50 weeks a year.

ii) Operating Materials

The operating materials for an electrostatic precipitator include water and detergent used to clean the collection plates. It has been assumed that the required fresh water be available through existing pipes. Detergent is considered to be the only operating material that would have to be purchased. The cost for detergent consumed during a year of operation is estimated to be $100.

iii) Maintenance

The annual operating costs associated with maintenance consist of a labour and a material component. To reflect the higher wage rate of a maintenance worker, a 10% increase to the WR was applied. To account for the maintenance materials consumed by the worker (ie. duct tape, small tools etc.) a factor of 100% was applied to the WR. On this basis then, the Maintenance Cost (MC) was determined using the following equation:

$$MC = (WR + 1.1\ WR) \times t \times d \qquad (7.5)$$

The daily requirement for maintenance was estimated to be one half hour. The estimation may be considered high for a small unit, but previous use of precipitators in Union Carbide mines have shown that a high frequency of maintenance can be required (Swindle, not dated).

iv) Replacement Materials

It is anticipated that the major part requiring replacement will be the ionizer wires at $50 for a 100 m roll (N.R. Murphy, 1985). However, there is also the possibility of damaging a power pack as a result of high humidity in an underground mine. The replacement of a power pack would cost approximately $140 (N.R. Murphy, 1985). For purposes of this report, a value of $400 will be used as the cost of replacement materials.

v) Waste Treatment and Disposal

The waste treatment and disposal cost has been assumed to be zero. This assumption is based upon the fact that the collected material can be added to mine wastes and will not require further treatment and that the manpower allotment for the disposal task can been accounted for in the operator labour cost.

7.2.2 Indirect Operating Cost

The indirect operating cost, shown in Table 7.3, consists of overhead, insurance and administration, and amortized capital cost.

i) Overhead

There are two categories of overhead-payroll and plant. The payroll overhead includes those expenses directly associated with operating and maintenance labour, such as workmen's compensation, social security contributions, vacations, group insurance, and other fringe benefits (Calvert and Englund, 1984). The plant overhead would account for those expenses not necessarily tied to the plant operation and maintenance of the control system. Examples of plant overhead are plant protection, employee amenities, and lighting.

Traditionally, the payroll and plant overhead have been combined into one figure and computed as a percentage of the total annual operating and maintenance labour cost. In this study, the overhead was included in the labour rate, WR.

ii) Insurance and Administration

The insurance and administration costs were taken as 1 and 2%, respectively, of the installed capital cost (A + B) (Calvert and Englund, 1984). The administration term covers sales, research and development, accounting, and

other home office expenses.

iii) Amortized Capital Cost

The Amortized Capital cost, AC, "spreads out" the initial investment over the life of the system. The cornerstone of this method is the Capital Recovery Factor (CRF), which when multiplied by the Total Installed Cost (TIC), yields an annual payment that accounts for the original investment and the cost of borrowing.

$$CRF = \frac{i\,(1 + i)^n}{(1 + i)^n - 1} \qquad (7.6)$$

where i is the appropriate interest rate and n the useful life of the equipment (yr). An interest rate of 12% will be used in this study, a value which is believed to representative of the Canadian situation. The average life expectancy of an electrostatic precipitator is 20 years (Calvert and Englund, 1984). However, because of the harsh working environment of a mine and the average life expectancy of the mine (10 years), a life expectancy of 10 years for an electrostatic precipitator was used.

Substituting the values of 12% and 10 years for i and n into equation 7.6 results in a CRF value of 0.18. The overall amortized capital cost is therefore

$$AC = 0.18\ (TIC) \qquad (7.7)$$

The Annual Operating Cost (AOC) can now be written as

$$AOC = 8625 + 0.03\ (A + B) + 0.18\ (TIC) \qquad (7.8)$$

Table 7.4 presents the AOC values for the different precipitator control units. So that the different control units can be compared on common ground, the calculated efficiency (using the generic model) described in Section 5.1.3 is also presented in Table 7.4.

Table 7.4

CALCULATED TOTAL OPERATING COST (AOC)

Control Unit	Calculated * Efficienty (%)	AOC (thousands of dollars)
Aquatron 15-4-3-2	79.9	17.30
IP - 14/2	73.3	17.81
ECU -10-55	77.7	20.56
Tabular	94.7	30.37

* calculated efficiency for removal of condensation nuclei at a flow rate of 7.0 m^3/s.

8.0 THE EFFECTS OF THE USE OF ELECTROSTATIC PRECIPITATORS ON RADIATION EXPOSURE AND DOSE

8.1 Current Exposure Conditions for Canadian Underground Uranium Mines

Information on exposures of radiation workers in Canada can be found in the National Dose Registry maintained by the Radiation Protection Bureau of Health and Welfare Canada. Information on uranium miners published from this source (e.g. Health and Welfare Canada, 1983) does not distinquish between underground or open pit mines, and may include exposures to mill workers as well as miners. For this reason, published information on annual exposure from less extensive but more specific references was gathered for this chapter of the report.

Ching et al (1984) analysed the gamma doses and radon daughter exposures of some Canadian uranium mine workers in 1982 and 1983. For two Ontario underground mines, the average radon daughter exposures ranged from 1.08 to 1.48 WLM/y. A separate analysis of company records showed average radon daughter exposure values in 1983 of 1.02 WLM/y and 1.04 WLM/y for two Elliot Lake mining companies (Lowe et al., 1984). The exposures in Elliot Lake mines are measured using the conventional modified Kusnetz method which does not discriminate on the basis of particle size or attached/unattached fraction.

As noted by Ching et al. (1984), individual exposure records for long-lived radioactive dust and thoron daughters are not available. However, measurements by Duport and Edwardson (1984) of the air concentrations of alpha emitting dust ranged from 10 to 700 mBq/m^3 in underground locations (about 1 mg/m^3 total dust). These levels result in an average effective dose of about 10 mSv/y (Ching et al., 1984). The average concentration of thoron daughters in Elliot Lake mines is about equivalent to the radon daughter concentration (Lowe et al., 1984). Such dust and thoron exposures may have significant influences on any new proposed regulations that attempt to sum the total radiological risks to uranium miners.

No published literature on the exposures levels in Amok underground operation at Cluff Lake is available at this time.

8.2 Aerosol Characteristics Affecting Radiation Dose

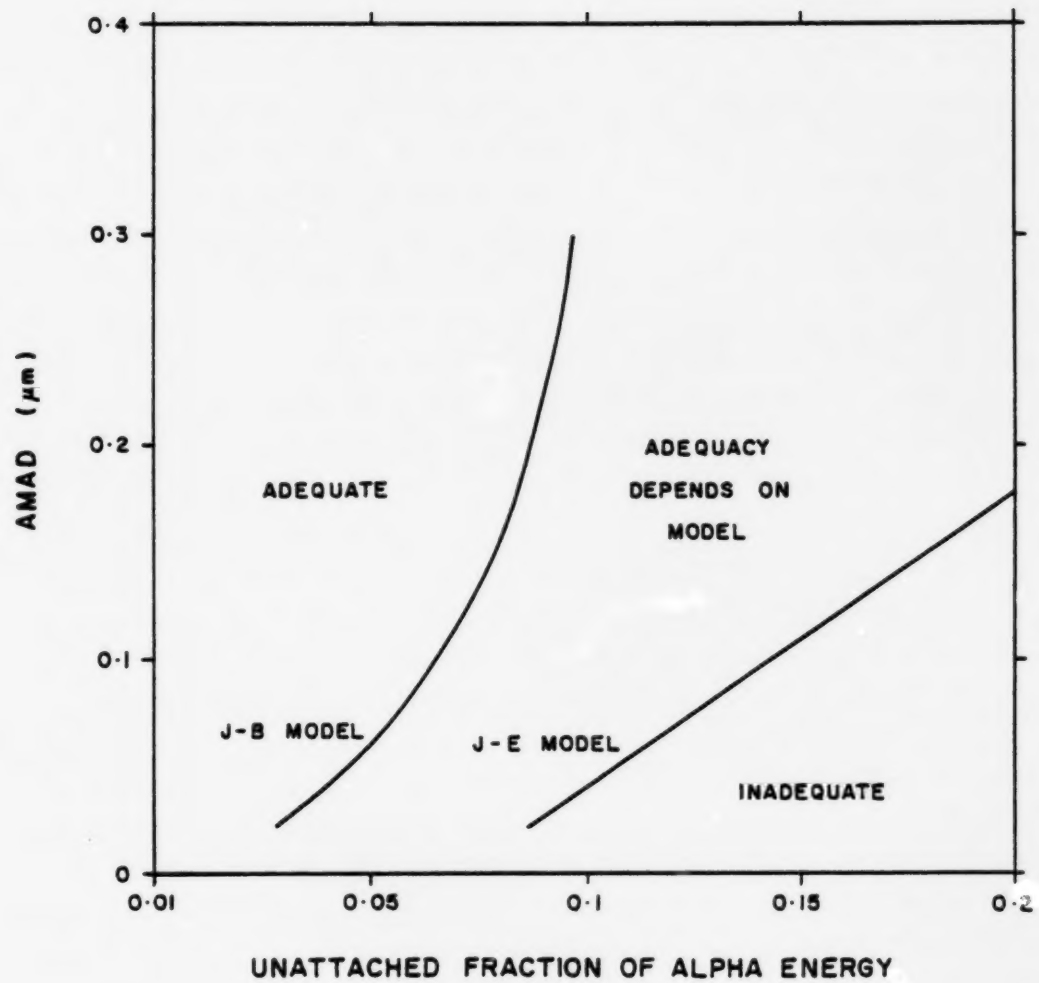
The radiological impact of exposure to a given atmosphere is only partly determined by the concentration of airborne radionuclides (Jonassen, 1984). Other factors that affect the likelihood of inhalation, deposition in the nose or lung, and retention in the body are also very important. For underground uranium mines, two factors of concern are the attached/unattached fraction of radon and thoron daughters, and particle size. For example, according to the ICRP lung deposition model, inhaled unattached decay products are almost totally retained in the respiratory system, whereas only about 20 to 40% of 0.1 μm particles (the attached fraction) are retained. This suggests that the retention of unattached decay products in the respiratory system may be 2.5 to 5 times greater for unattached decay products than for attached decay products (Hinds et al., 1982).

The dosimetry of inhaled radionuclides is extremely complex and much literature is available on this topic. Since a lengthy review of this material is beyond the scope of this report, it was considered sufficient to summarize the results of authoritative reviews on this subject.

Johnson, reporting in SENES (1984), conducted an extensive review of the dosimetry of radon daughters. He investigated several lung models and many parameters such as breathing rate, particle size and attached/unattached fraction. Using a criterion that the WLM to rem (effective dose equivalent) ratio should not exceed 1.5 times the nominally accepted value of 1 rem (10 mSV) per WLM, Johnson developed Figure 8.1 which gives the values of particle size and unattached fraction for which this criterion is or is not satisfied. Johnson concluded that the particle size and unattached fraction encountered in most underground mine workplaces fall in the adequate region. (As noted earlier in this report, the long-term average for the unattached fraction in mines is generally below 0.05). As illustrated in Figure 8.1, should the use

FIGURE 8·1

ADEQUACY OF WLM AS A MEASURE OF RISK



NOTE:

1. COMBINATION OF PARTICLE SIZE AND UNATTACHED FRACTION OF ALPHA ENERGY FOR WHICH THE WLM IS AN ADEQUATE MEASURE OF RISK

SOURCE: SENES, 1984

of any filtration device greatly increase the unattached fraction above 0.1, the WLM unit would begin to significantly underestimate worker exposure to radon daughters. However, this is not likely to be a problem when using electrostatic precipitators since, according to Pourprix et al. (1984), one can assume that the unattached fraction is 100% removed by an electrostatic precipitator.

Johnson (1984) also reviewed in detail the dosimetry of inhaled long-lived alpha activity in ore dust. His calculations show that the calculation of annual limit on intake for uranium ore dust yields results that can range from 1600 to 4500 Bq for 1 μm AMAD aerosols. Johnson (1984) has also examined the effect of particle size and concludes that a value of 3000 Bq for uranium would be appropriate for radiation protection purposes for aerosols in the range of 2 to 5 μm. This particle size range is thought to be more representative of aerosols in mines than the 1 μm used by the ICRP (Duport and Edwardson, 1984). Because of the uncertainties and variability in the many parameters required in the dosimetric evaluation of aerosols, it is difficult to assess with much accuracy the effects on dose of the removal of long-lived aerosols by electrostatic precipitators. However, any reduction in the concentration of respirable aerosols will lead to a reduction in dose.

8.3 Relationship Between Efficiency, Exposure Reduction, and Cost

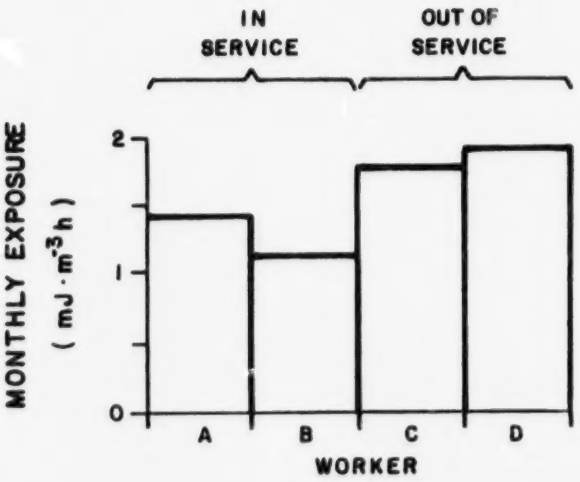
8.3.1 Observed Reduction in Exposure Levels in French Mines

In the French pilot studies the monthly exposure of individual workers (mJ/m^3h) was studied. Figure 8.2 presents the results for the eight workers studied as a function of precipitator operation and number of precipitators (Morel et al., 1982). The mean reduction in the monthly exposure was 35% with two precipitators and 41% with three precipitators.

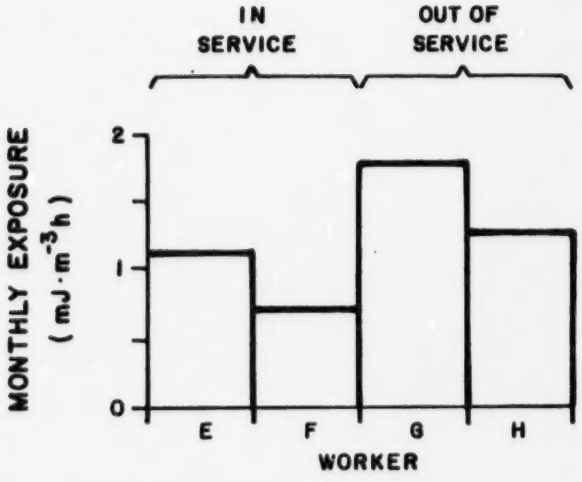
The large variation between the exposure of the individual worker, under the same operating conditions, is the result of fluctuations in alpha energy with time and the different locations of the workers within the mine.

FIGURE 8·2

INDIVIDUAL DOSIMETRY RESULTS FOR EIGHT WORKERS



A) TWO PRECIPITATORS



B) THREE PRECIPITATORS

NOTE:

DURATION OF EXPERIMENT WAS MARCH 1 THROUGH MARCH 12, 1982
DURATION OF EXPERIMENT WAS FEBRUARY 15 THROUGH FEBRUARY 27, 1982

$\frac{1 mJ \cdot h}{m^3}$ = 0.285 WLM

SOURCE: ADAPTED FROM MOREL et al, 1982

Dosimeters were also used to determine the monthly exposure levels at different locations of the auxiliary ventilation flow to a stope. In Figure 8.3 the exposure levels, with and without purification are shown at various locations: before the precipitator; after the precipitator; at the exit of the vent tube; at the head of the stope; and in the return air. Figure 8.3 also shows that no substantial in-growth of radon daughters has occured in the vent tube.

When three precipitators were used in a similar set-up as Figure 8.3, the purification efficiency was 80% between the upstream and the return air. No sampling was performed at the exit of the vent tube or head of the stope (Morel et al., 1982).

8.3.2 Cost and Exposure Reduction

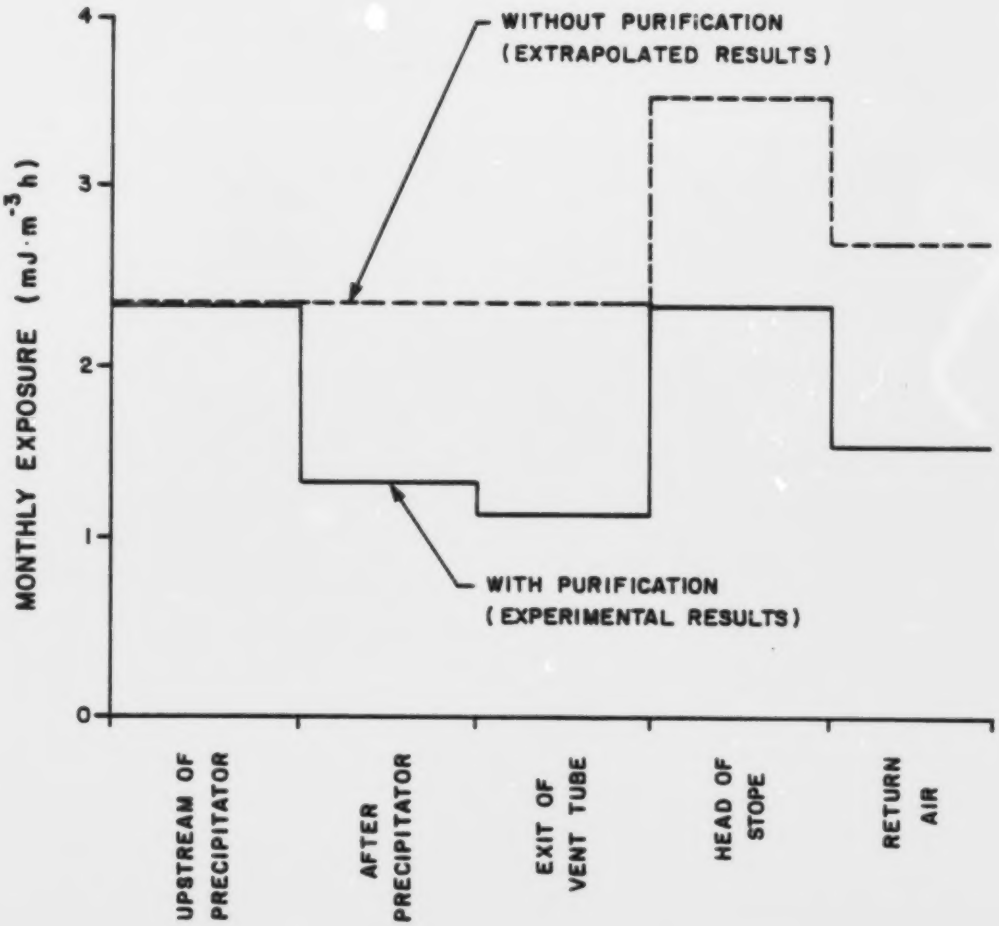
In Table 8.1 inputs for the generic model, introduced in Chapter 5 and described in Appendix B, representing three models of precipitators are presented. The assumed flow rate of 7 m^3/s is representative of auxiliary flow rates in Canadian mines.

The calculated percent reduction in total alpha potential is also presented in Table 8.1. Since a working level (WL) is directly proportional to the total alpha potential (mJ/m^3) their percent reduction is the same. Similarly since a miner's exposure in working level months (WLM) is directly proportional to exposure conditions in the workplace (WL) the percent reduction in exposure to a miners working full time in purified air is also the same.

The Total Annualized Cost (TAC)/Percent Dose Reduction (PDR) ratio for the three models are presented in Table 8.2. From these values, it can be concluded that for the conditions examined, an investment of approximately Ω262 per year would lead to a reduction of one percent in the exposure of a miner breathing the purified air for his full underground work time. (It should be noted that this is somewhat artificial since no reduction could be

FIGURE 8·3

DOSIMETRY RESULTS USING TWO PRECIPITATORS



NOTE:

$1 \frac{mJ \cdot h}{m^{-3}} = 0{\cdot}285$ WLM

SOURCE: ADAPTED FROM MOREL *et al*, 1982

Table 8.1

INPUTS/OUTPUTS FOR GENERIC MODEL

Parameters	Equipment			
	Aquatron (15-4-3-2)	IP (14/2)	ECU (10-55)	Tabular
Specifications:				
Flow rate (m^3/s)	7.0	7.0	7.0	7.0
Face area (m^2)	2.23	2.64	2.60	3.54
Collecting area (m^2)	68.0	81.1	80.0	91.4
Collecting field (KV/m)	903.0	632.0	898.0	984.0
Ionizing charge (KV/m)	545.0	523.0	426.0	656.0
Calculated Efficiencies:				
Total alpha potential (%) (radon daughters)	79.9	73.3	77.7	94.7
Percent Dose Reduction (PDR)	79.9	73.3	77.7	94.7

Table 8.2

COST AND DOSE REDUCTION*

Parameters	Equipment: Aquatron (15-4-3-2)	IP (14/2)	ECU (10-55)	Tubular
Annual Operating Cost AOC (thousands of dollars)	17.30	17.81	20.56	30.37
Percent Dose[2] Reduction, PDR (%WL)*	79.9	73.3	77.7	94.7
AOC/PDR (Ω/%WL)*	217	243	265	321

Notes

1. From Table 7.4

2. From Table 8.1

* see text

achieved without the installation and operation of the precipitator in the first place. The TAC/PDR ratio must be viewed in this context. Whether or not such expenditures could be considered cost effective require a workplace by workplace analysis and is beyound the scope of this report.

9.0 SUMMARY ASSESSMENT

9.1 Effectiveness and Problems

The review of reported experience with the use of electrostatic precipitators, particularly the French pilot studies, indicates that electrostatic precipitators can effectively reduce the concentration of radioactive aerosols in underground uranium mines.

The major problems encountered while using a precipitator in an underground mine were electrical in nature, such as sparking and electrical short circuits, which occurred under conditions of high relative humidity. These problems can be overcome by using lower charging voltages (which would reduce the collection efficiency), current limiters to protect the power packs, and properly sealed equipment.

Other problems encountered included ionizer wire breakage, high cleaning frequency, and interference in equipment movement because of the size and location of precipitators. Through the use of modern precipitators which employ thicker ionizer wires, prefilters and better wash sections, and the cutting away of a drift wall to accommodate the extra space required by the precipitators, these problems can be overcome but with a corresponding increase in cost.

9.2 Possible Use and Type

The potential use of an electrostatic precipitator in an underground mine is to treat some or all of the air entering a work area or work station. Examples of work areas are dead-end stopes, maintenance shops and lunch rooms. A work station refers to an area of a stope in which workers are present. Once the air has been treated it would then pass through a vent tube directly to the workers.

The possible location of an electrostatic precipitator is a function of the

mine's configuration and air flow rates. For mines which have open stopes that are ventilated with primary ventilation, the precipitator can be located inside the stope to treat the air being directed to a particular work station. When a work area is being ventilated with auxiliary ventilation, the precipitator can be located in the adjacent drift passage.

A two-stage precipitator employing a positive corona is the type of precipitator which can be used for the treatment of ventilation air in an underground uranium mine. This type of precipitator produces less ozone than a precipitator with a negative corona.

9.3 Cost and Exposure Reduction

The Annual Operating Cost, AOC, for a control unit to treat an auxiliary ventilation flow of about $7m^3/s$, typical of auxiliary flow rates in Canadian uranium mines, with a condensation nuclei removal efficiency of 73 to 95%, is approximately $17,300 to $30,370, depending upon the precipitator model. (These costs do not include special design features which may be required for particular applications or the costs of cutting away a drift wall to make space and other such items which vary with application.

In terms of cost and a Percent Dose Reduction, PDR (%WL), the AOC/PDR has been estimated to be approximately $262. That is, assuming a linear scale for comparative purposes, a $262 expenditure is required per year for every 1% reduction in working level at a work station.

The actual costs and benefits (in terms of exposure reduction) would vary with the mine and with the application. The cost effectiveness of using a precipitator can only be determined by analyzing each workplace on an individual basis.

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GLOSSARY

AMAD — Activity Median Aerodynamic Diameter is the particle diameter (expressed as equivalent aerodynamic diameter) below which 50% of the activity in an aerosol distribution is contained. Particle size distribution curves commonly conform to a lognormal distribution in which case the median value is also the geometric mean.

Condensation Nuclei

Small particles which serve as nuclei to initiate further processes, namely condensation and coagulation (NRC, 1978)

EAD — Equivalent Aerodynamic Diameter is the diameter of a spherical particle of density 1 g/cm^3 which has the same terminal settling velocity as the sampled particle (Bigu and Grenier, 1985).

LLRD — Long Lived Radioactive Dust in a uranium mine environment is dust containing long-lived radioisotopes (U-238, U-235 and Th-232 and some of their decay products).

MMAD — Mass Median Aerodynamic Diameter is the particle diameter (expressed as equivalent aerodynamic diameter) below which 50% of the mass in an aerosol distribution is contained. Since activtiy is not necessarily related to particle mass, the AMAD and the MMAD may be different.

WL — Working Level is any combination of short-lived radon decay products (through ^{214}Po) in 1 liter of air that will result in the ultimate emission of 1.3×10^5 MeV of alpha energy.

WLM — Working Level Month is unit of exposure equal to exposure to a concentration of 1 WL for a duration of 170 hr (one working month).

APPENDIX A

SURVEY RESULTS

Table A.1

LIST OF COMPANIES CONTACTED (BY MAIL AND PHONE)

AAF-Canada
Aercology Inc.
Air Correction Division UOP Inc.
Air Quality Division (Dustex/Apitron)
Airtech Systems Inc.
Anderson 2000 Inc.
Beltran Associates Inc.
Brown Boveri Corp.
Cambridge Filter Corp.
Car-Mon Products
Ceilcote Co., The A Unit of General Signal
Chemithon Corp.
Combustion Power Co. Inc.
Coors Porclean Co.
Davis Energy Systems
Del Electronics Corp.
Dustex Corp.
EFB Inc.
Eltron Manufacturing Co.
Engelhard Industries
Environmental Elements Corp.
Flakt Canada Ltd.
F.L. Smidth & Co.
General Electric Environmental Services, Inc.
Joy Manufacturing Co.
Koppers Co. Inc.
Lodge-Cottrall, Dresser Industries Inc.
Metal Cladding Inc.
Mikropul Corp., Ashland Technology Corp.
Neundorfer Engineered Equipment
NKK America Inc.
N.R. Murphy Ltd.
Research-Cottrell (Air Pollution Control Division)
Sourcex (Nederman)
Trion
United McGill Corp., McGill Precipitator System
United Air Specialists Inc.
Westinghouse

Table A.2

COMPANY RESPONSES

Company	Potential Use *	Type of Precipitator
AAF-Canada	YES	"ECU" Parallel plate, two-stage, electrostatic precipitator.
Beltran Associates Inc.	YES	Tubular electrostatic precipitators of two-stage design. Can run continuously or intermittently wet.
Car-Mon Products Inc.	NO	Produce ventilation type of precipitators but their largest is too small, (1500 cfm).
Ceilcote Co.	NO	"Ionizing Wet Scrubber" Do not produce an electrostatic precipitator.
Chemithon Corp.	NO	"Chemithon HITEC" This precipitator is designed primarily for use with sulfonation plants.
Davis Energy Systems	YES	"IP Air Cleaners" Two-stage electrostatic precipitator.
Dustex Corp.	NO	Only produce an electrostatically augmented fabric filter, the Apitron.
Englehard	NO	Do not produce electrostatic precipitator
Flakt Canada Ltd.	NO	Single-stage design for industrial vent gases. Do not produce ventilation type precipitators.
F.L. Smidth & Co.	NO	Single-stage design, with negative polarity. Used for industrial vent gases.
General Electric	NO	Single-stage precipitators for industrial vent gases. High CFM and dust particle loading.
Joy Manufacturing Co.	NO	Produce only single-stage electrostatic precipitators.

* The response provided by the Company as to whether or not their precipitators have potential application in underground uranium mines.

Table A.2 cont'd

Company	Potential Use*	Type of Precipitator
Lodge-Cottrell (Dresser Industries Inc.)	NO	"Fluid Plate" or "Tubular" single-stage wet electrostic precipitator for vent gases
N.R. Murphy	YES	"Aquatron" Two-stage electrostatic precipitator.
Research-Cottrell (Air Pollution Control Division)	NO	Do not believe their electrostatic precipitator is the proper product for this application.
Sourcex (Nederman)	NO	Produce ventilation type precipitators but their largest is too small (500 cfm).
United McGill	NO	"McGill Intersept EP's" single-step electrostatic precipitators for vent gases.
Westinghouse	NO	No longer produce electrostatic precipitators.

* The response provided by the Company as to whether or not their precipitators have potential application in underground uranium mines.

APPENDIX B

EMPIRICAL MODEL

APPENDIX B

EMPIRICAL MODEL

B.1 Estimation of Effective Migration Velocity, W_e, from French Pilot Studies

In Tables B.1 to B.3, the calculated W_e values for the three French mines are listed. The W_e (m/s) values were calculated using the following equation, based on equation 5.1 (after Deutsch, 1922).

$$W_e = \frac{-V}{A} \ln (1-n) \qquad (B.1)$$

where V is the flowrate (m^3/s), A is the collection area (m^3/s), and n is the efficiency. The efficiency "n" substituted in B.1 is for the reduction in the potential alpha energy, E_a.

Table B.4 gives the calculated effective migration velocity which was based on the efficiency of removing condensation nuclei for data from the Betoule mine.

B.2 Factors Affecting Migration Velocity

As discussed in Section 5.3.1 (equation 5.5), the theoretical migration velocity can be represented by a function, f, where

$$W_e = f (E_p, u, r_p, \lambda, q) \qquad (B.2)$$

where E_p is the collecting field, u the gas viscosity, r_p the particle radius, λ the mean free path of the ambient gas molecule and q the particle charge.

Table B.1

DETERMINATION OF W_e FROM EFFICIENCY OF E_a REMOVAL IN THE BETOULE MINE

n (%)	V (m^3/s)	W_e (m/s)
88	1.1	0.149
72	1.1	0.090
52	1.5	0.070
60	2.0	0.117
36	2.0	0.057
42	2.5	0.087
32	2.5	0.062
27	2.5	0.050
23	3.0	0.050
30	3.5	0.080
21	3.5	0.053
14	3.5	0.034

Notes

E_a is the potential alpha energy

Reference

Pourprix et al., 1982

Table B.2

DETERMINATION OF W_e FROM EFFICIENCY OF E_a REMOVAL IN THE AKOUTA MINE

n (%)	V (m^3/s)	W_e (m/s)
59	1.85	0.105
52	1.85	0.087
37	3.00	0.090
34	3.00	0.081
56	3.2	0.168
45	3.2	0.122

Notes

E_a is the potential alpha energy

Reference

Pourprix et al., 1982

Table B.3

DETERMINATION OF W_e FROM EFFICIENCY OF E_a REMOVAL IN THE CHARDON MINE

n (%)	V (m^3/s)	W_e (m/s)
87	0.90	0.117
78	0.90	0.087
73	0.90	0.075
73	1.30	0.109
67	1.30	0.092
44	1.30	0.048
24	2.55	0.045
21	2.55	0.038

Notes

E_a is the potential alpha energy

Reference

Pourprix et al., 1982

Table B.4

DETERMINATION OF W_e FROM EFFICIENCY OF CONDENSATION NUCLEI REMOVAL FOR THE BETOULE MINE

n (%)	V (m^3/s)	W_e (m/s)
92	0.5	0.081
87	0.75	0.098
81	1.00	0.106
78	1.05	0.102
77	1.11	0.104
74	1.25	0.108
67	1.48	0.105
64	1.50	0.098
59	1.75	0.100
53	1.98	0.096
50	2.0	0.089
48	2.05	0.086
45	2.5	0.096
39	2.65	0.084
36	2.65	0.076
31	3.05	0.072
27	3.30	0.066

Reference

Pourprix et al., 1982

Substituting the parameters required to estimate q, derived from equation 5.3, into equation B.2 gives

$$W_e = f\,(E_p,\ u\ r_p,\ \lambda,\ \beta,\ E_o,\ t,\ N_o,\ e,\ K) \qquad (B.3)$$

where β is an empirical constant, E_o is the ionizing field strength, t is the charge time, N_o is the ion concentration, e is the electronic charge and K is the electrical mobility of the ions.

Several parameters can be assumed to be constant when comparing different types of electrostatic precipitators and the two mine environments, French and Canadian. Examples of these are the gas viscosity, u, mean free path of ambient gas molecule, λ, the electrical mobility of the ions, K, ion concentration, N_o, and the particle radius, r_p. These assumptions are based upon 1) similar temperature and relative humidities, 2) similar aerosol concentrations (approx. 1×10^5 nuclei per cm^3) and 3) similar mean mass diameters of the particles (France, 3.6 μm; Canadian, 2-10 μm).

By collecting the constants β and e and the "constant" parameters (u, λ, K, N_o, r_p) into an overall empirical parameter, F, equation 5.3 can be further simplified.

The overall equation for the effective migration velocity can then be determined by combining equations 5.3 and equation 5.5 and then inserting F.

$$W_e = F\ E_p\ E_o\ \frac{t}{t + 4.02 \times 10^{-3}} \qquad (B.4)$$

The constant 4.02×10^{-3} is equal to the product of N_o (2.5×10^8 ions/cm^3), e (4.8×10^{-10} esu cgs), K (660 esu cgs) and π as per equation 5.3. These parameters are assumed to be constant for different precipitators and mines (French or Canadian).

The charge time, t (sec), is a function of the depth of the corona discharge

area, D (m), and the face velocity, v (m/s). The latter is calculated from the air flow, V (m^3/s), and face area, A_f (m^2). The face area is the cross sectional area perpendicular to the gas flow at the entrance of the precipitator, thus

$$t = \frac{D}{v} = \frac{D}{V/A_f} \qquad (B.5)$$

An assumption that the depth of the corona discharge area is approximately the same between precipitators will be made. The value from an AAF ECU unit of 6.6×10^{-2} m will be used in the equation.

B.3 Determination of Equation to Calculate W_e

It was shown in the previous section that the theoretical migration velocity is a function of three main parameters; E_p, E_o and t. By substituting in equation B.5 for t in equation B.4, the effective migration velocity is equal to

$$W_e = F\, E_p\, E_o \; \frac{\frac{6.6 \times 10^{-2}\, A_f}{V}}{\frac{6.6 \times 10^{-2}\, A_f}{V} + 4.02 \times 10^{-3}} \qquad (B.6)$$

where F is an empirical factor which is independent of the particular two-stage precipitator used or whether it is a Canadian or French mine.

To determine F, the values of W_e reported in section B.1 and the corresponding flow rates, V, were used.

The field strengths, E_p and E_o, of the ELOSTA 4000, the precipitator used in the French mines, were 672 $\frac{KV}{m}$ and 452 $\frac{KV}{m}$.

The face area of this precipitator was 0.33 m^2 (Pourprix et al., 1982). Substituting these values into equation B.6 results in

$$F = \frac{W_e}{3.04 \times 10^5} \quad \frac{\frac{2.18 \times 10^{-2}}{V}}{\frac{2.18 \times 10^{-2}}{V} + 4.02 \times 10^{-3}} \qquad (B.7)$$

Two types of empirical factors were calculated. F_1 was determined from data on the efficiency of reducing potential alpha energy and F_2 was determined from data on the efficiency of removing condensation nuclei. Tables B.5 and B.6 list the calculated F values.

For the Betoule, Akouta and Chardon mines the F_1 values were 3.45×10^{-7}, 5.27×10^{-7} and 3.1×10^{-7}, respectively. The average of the three values was 3.94×10^{-7}. The average F_2 value calculated from Betoule mine data, was 4.0×10^{-7}. An overall F value of 4×10^{-7} will be used when calculating the efficiency of condensation nuclei removal and the percent reduction in potential alpha energy.

The overall, general, equation for W_e is now

$$W_e = 4 \times 10^{-7} E_p E_o \quad \frac{\frac{6.6 \times 10^{-2} A_f}{V}}{\frac{6.6 \times 10^{-2} A_f}{V} + 4.02 \times 10^{-3}} \qquad (B.8)$$

Table B.5

DETERMINATION OF F_1

Mine	W_e (m/s)	V (m^3/s)	F_1*	
Betoule	0.149	1.1	5.90×10^{-7}	
	0.090	1.1	3.56×10^{-7}	
	0.070	1.5	2.94×10^{-7}	
	0.117	2.0	5.27×10^{-7}	
	0.057	2.0	2.57×10^{-7}	
	0.087	2.5	4.19×10^{-7}	$F_B = 3.45 \times 10^{-7}$ Avg
	0.062	2.5	2.98×10^{-7}	
	0.050	2.5	2.41×10^{-7}	
	0.050	3.0	2.56×10^{-7}	
	0.080	3.5	4.33×10^{-7}	
	0.053	3.5	2.87×10^{-7}	
Akouta	0.105	1.85	4.65×10^{-7}	
	0.087	1.85	3.84×10^{-7}	
	0.090	3.00	4.60×10^{-7}	
	0.081	3.00	4.14×10^{-7}	$F_A = 5.27 \times 10^{-7}$ Avg
	0.168	3.2	8.80×10^{-7}	
	0.122	3.2	6.39×10^{-7}	
Chardon	0.117	0.90	4.49×10^{-7}	
	0.087	0.90	3.34×10^{-7}	
	0.075	0.90	2.88×10^{-7}	
	0.109	1.30	4.45×10^{-7}	
	0.092	1.30	3.76×10^{-7}	$F_C = 3.11 \times 10^{-7}$ Avg
	0.048	1.30	1.96×10^{-7}	
	0.045	2.55	2.18×10^{-7}	

F_1 avg = 3.94×10^{-7}

Note

* see text

Table B.6

DETERMINATION OF F_2

W_e (m/s)	V (m^3/s)	F_2 *
0.081	0.5	2.91×10^{-7}
0.098	0.75	3.67×10^{-7}
0.106	1.00	4.13×10^{-7}
0.102	1.05	4.01×10^{-7}
0.104	1.11	4.13×10^{-7}
0.108	1.25	4.38×10^{-7}
0.105	1.48	4.40×10^{-7}
0.098	1.50	4.12×10^{-7}
0.100	1.75	4.36×10^{-7}
0.096	1.98	4.32×10^{-7}
0.089	2.0	4.01×10^{-7}
0.086	2.05	3.90×10^{-7}
0.096	2.5	4.62×10^{-7}
0.084	2.65	4.12×10^{-7}
0.076	2.65	3.73×10^{-7}
0.072	3.05	3.76×10^{-7}
0.066	3.30	3.50×10^{-7}

F_2 avg = 4.0×10^{-7}

Note

Results are for the Betoule mine.

* see text

```
5  '
7  ' MODEL "EFF.BAS"
8  '
10 ' EMPIRICAL MODEL FOR THE EFFICIENCY OF A PRECIPITATOR IN
20 ' AN UNDERGROUND URANIUM MINE
30 '
32  ' PREPARED BY J.D. PHYPER OF SENES CONSULTANTS LIMITED
33  ' FOR THE A.E.C.B., DECEMBER 7TH, 1985
34 '
36 '
50   INPUT "TYPE OF PRECIPITATOR";XA$
55   INPUT "FACE AREA (M2)";AF
60   INPUT "COLLECTING FIELD (KV/M)";EP
65   INPUT "IONIZATION CHARGE (KV/M)";E0
70   INPUT "FLOW RATE (M3/S)";V
73   INPUT "COLLECTING AREA (M2) ";A
74   INPUT "WORKING LEVEL";WL
75 '
80 ' CONSTANTS
85 '
87 ' EMPIRICAL FACTOR
90   F =  .0000004
100 '
105 'CALCULATION OF THE EFFECTIVE MIGRATION VELOCITY
107 '
110  K = .066*AF/V
120  WE = F*EP*E0*( K/( K+.00402))
135  EFF =100*(1 - EXP(-(A*WE)/V))
136 '
139   PRINT "EFFECTIVE MIGRATION VELOCITY (M/S)=";WE
140   PRINT "REMOVAL EFFICIENCY (%)=";EFF
141 '
142   WLN = WL*(1-EFF/100)
143 '
145   INPUT "OUTPUT, Y=1,N=2 ";OP
146   IF OP = 2 THEN 180
147 '
148   LPRINT "INPUTS"
149   LPRINT "TYPE OF PRECIPITATOR =";XA$
151   LPRINT "COLLECTING FIELD (KV/M) =";EP
152   LPRINT "IONIZING CHARGE (KV/M) =";E0
153   LPRINT "FLOW RATE (M3/S) =";V
154   LPRINT "FACE AREA (M2) =";AF
155   LPRINT "COLLECTING AREA (M2) =";A
162   LPRINT " "
163   LPRINT "OUTPUTS"
165   LPRINT "EFF. FOR CONDENSTATION NUCLEI/TOTAL ALPHA POTENTIAL(%)=";EFF
170   LPRINT "PREVIOUS WORKING LEVEL ";WL
175   LPRINT "NEW WORKING LEVEL =";WLN
180   STOP
```